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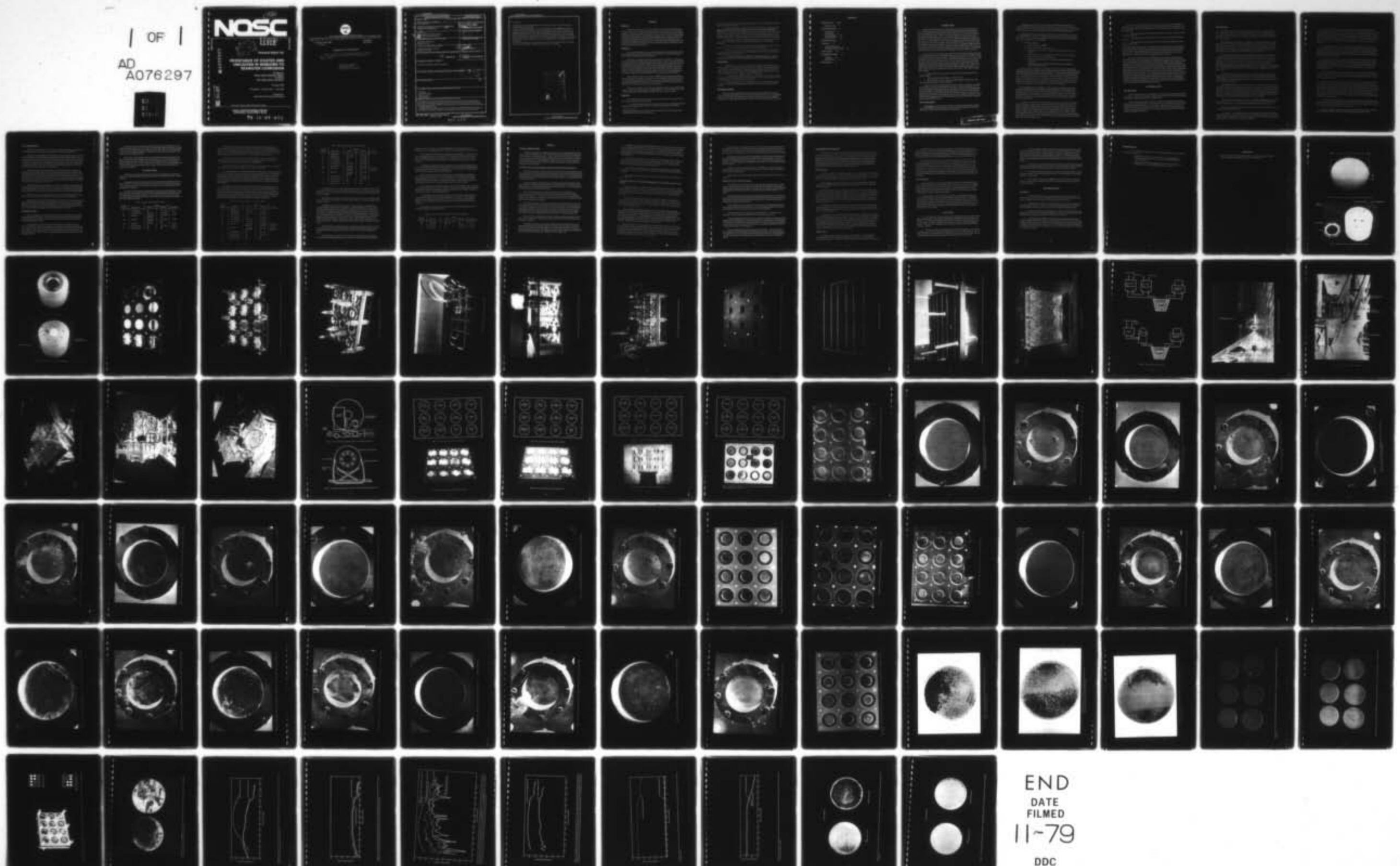

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RESISTANCE OF COATED AND UNCOATED IR WINDOWS TO SEAWATER CORROSION

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Germanium and chalcogenide glass specimens were submerged to a 35-foot depth in San Diego Bay for 4 months and the deterioration of their surfaces noted. Some of the specimens were bare, some were protected with a single-layer anti-reflective (AR) IR coating, the remainder were coated with either polyolefine, polyethylene, or polypropylene plastic surcoat.

To simulate different operational scenarios to which a submarine-mounted IR window may be subjected, some of the specimens were exposed to natural water circulation, others to water velocities of 6 feet per second.

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20. Continued.

Additionally, some of the submerged specimens were heated by an electric current to simulate de-icing procedures in an arctic environment.

Unprotected germanium was found to corrode rapidly while chalcogenide AMTIR-1 glass exhibited excellent corrosion resistance. All plastic surcoats failed by separation from the specimens due to presence of pinholes and water permeability. Anti-reflective coatings deteriorated also, but the transmission of the best single layer AR coating tested (Exotic Materials No. 40104) decreased only five percent, even though presence of pinholes in the coating generated many shallow (< 0.010 inch) corrosion craters in the surfaces of the germanium specimens. Passage of electric current through germanium accelerated the rate of corrosion; one hour of current flow produced more corrosion to the wetted window surface than 8000 hours without electric current.

Next phase of testing will cover not only improved single layer, but also durable multilayer AR coatings that promise to extend the life of germanium windows in seawater to 12 months.

SUMMARY

PROBLEM

Germanium windows are to be used on submarine-mounted infrared (IR) imaging systems and as such, the windows will be immersed in seawater during most of their operational life. Germanium corrodes in seawater, therefore, it is necessary to develop a method of protecting the germanium. This method of protection, however, must not interfere with, but rather, if feasible, assist the function of the imaging systems. Therefore, the protective coating on the external surface of the window must not impede, but enhance the transmission of electromagnetic radiation in the 7- to 13-micron spectral wavelength range. Also, it is desirable that the selected coating retard the biological fouling of the windows, which otherwise would reduce transmissivity.

APPROACH

An experimental approach to the problem was taken involving the testing, in conditions approximating actual submarine missions, of various types of coatings on specimens fabricated from germanium and chalcogenide glass.

Specifically, the conditions under which specimens were tested were: Exposure to seawater with natural circulation induced by tidal currents; exposure to seawater with forced circulation generated by a submersible pump; and exposure to seawater while the specimen was heated by electrical resistance heating. Forced circulation was utilized in one part of the test to determine whether or not it would discourage biological fouling. Electrical resistance heating was utilized in another part of the test because it was one method shown effective in previous testing for keeping the window free of ice in a sub-zero temperature environment, which otherwise would totally block the transmission of infrared light.

The specimens tested were of six types: AMTIR glass and uncoated germanium as control specimens; germanium coated with the Exotic Materials and Optic Electronic single layer IR anti-reflection coatings; and the plastic surcoats of polyethylene/polypropylene/polyethylene (PE/PP/PE) from Honeywell, and polyolefin (PO) polymer from Lane Instruments, both over an anti-reflection coating on germanium.

There were two phases to the testing, the preliminary indoor electric current testing in June and July 1978, and the primary fouling testing from 27 July to 11 December 1978, in the San Diego Bay off Berthing Pier 160, NOSC, Bayside, at a 35-foot depth.

RESULTS

The following information* was obtained from the tests where only a single face of the test specimens was wetted by seawater:

1. Uncoated germanium corrodes when exposed to seawater, exhibiting reasonably uniform surface etching. After 120 days of submersion the transmission of coherent

*All transmission measurements were performed on specimens which had their wetted surfaces cleaned and dried after removal from the ocean environment.

radiation in the 8- to 12-micron wavelength range through the uncoated germanium specimen decreased by almost 100 percent.

2. Germanium specimens coated with anti-reflection coatings corrode to varying degrees depending on the particular coating. The specimens with the Exotic Materials' single-layer anti-reflection coating sustained the least amount of damage of any of the coated specimens. These specimens also exhibited the least drop in transmission after exposure to seawater. After 120 days submersion in seawater, the transmission through specimens with EM #40104 and OE XF 27 single-layer AR coatings decreased 5 and 22 percent, respectively.

3. The specimens protected with plastic in addition to any anti-reflection coating also corroded. The plastic offered no noticeable added protection, and reduced the transmission.

4. Forced circulation reduced the amount of biofouling on the specimens' surfaces; however, in most cases it increased the rate of corrosion of the specimens.

5. None of the coated or uncoated germanium specimens held up well under electrical current testing. The plastics did well in the preliminary indoor tests, but all specimens corroded during the testing in the bay.

6. Uncoated chalcogenide glass AMTIR-1 (Amorphous Materials, Inc.) showed neither surface deterioration nor transmission loss after 120 days submersion in seawater.

CONCLUSION

1. Single-layer anti-reflective coatings deposited on germanium windows increase the transmission of electromagnetic radiation in the 7- to 13-micron wavelength range while at the same time protecting the surface of germanium from significant corrosive action of seawater for periods of up to 120 days. The best single-layer AR coating tested loses 5 percent of its original transmission capability during that time period.

2. Chalcogenide glass AMTIR-1 possesses excellent resistance to seawater corrosion and thus does not require any protective coatings on the wetted face. There was no decrease in transmission after a 120-day submersion in seawater.

3. Unprotected germanium corrodes rapidly in seawater. After 120 days of submersion, the transmission through germanium with a single corroded face decreased 100 percent.

RECOMMENDATIONS

Research on preventing corrosion to windows in ship-mounted IR systems should focus on two areas with high potential of return on the research investment: (1) chalcogenide glasses and (2) durable, hard, multilayer AR coatings. Both promise to provide negligible transmission losses through wetted windows in IR systems for at least a period of 12 months.

CONTENTS

INTRODUCTION

All infrared (IR) imaging systems operating in a marine environment require for their successful performance windows that, besides being transparent to infrared radiation, are also compatible with environmental parameters imposed by the marine environment. The environmental parameters inherent in submerged operations present a particularly difficult challenge to the designer of such a system as the window. For in addition to being transparent in the IR energy spectrum and resistant to saltwater corrosion, the system must also serve as a structural element of the pressure housing protecting the electro-optical imaging components from seawater intrusion. Because of the mismatch in coefficients of expansion, modulus of elasticity, and Poisson's ratios, the mating of a pressure-resistant IR window to a metallic pressure housing requires a high degree of design sophistication. This experience is rarely found unless mechanical engineers have previously acquired experience with pressure-resistant windows for electro-optical systems operating in the visible radiation spectrum.

Even windows that successfully carry the structural loads imposed on them by hydrostatic loading must still face the prolonged chemical attack of seawater on the highly polished surfaces exposed to the marine environment. Although germanium is not a very active chemical material, seawater reacts with it and forms soluble oxides and chlorides on its surface. For this reason, bare germanium windows cannot be used in marine service because the rough, corroded surface scatters and reflects incident thermal energy, significantly decreasing the magnitude of thermal signal strength transmitted through the window. The situation is not significantly different either for most anti-reflective (AR) coatings for germanium, or for plastic overlays placed over anti-reflective coatings. Thus, there are three options available to the designer:

1. Replace germanium with a more corrosion-resistant material transparent to infrared radiation.

2. Develop AR coatings with higher corrosion resistance.

3. Discover plastic overlays transparent to IR energy that will protect the AR-coated windows for longer periods of submersion.

All three options are promising approaches for prevention of corrosion on windows in IR imaging systems mounted on ships and submarines. If unlimited funding were available to the designer, all three approaches to corrosion prevention could be investigated as it is not known where a technological breakthrough might occur. Since unlimited funding is generally not the case, the research effort has to be focused on only one, or at most, two approaches to the problem. This report describes the study undertaken at NOSC to evaluate the potential for improvement in the three approaches for preventing window corrosion in marine environment IR systems.

STUDY PROCEDURE

The objective of the study was to evaluate, in the shortest possible time and with the least expenditure of funds, the potential return on the three approaches mentioned previously to extend the life of IR windows in marine service.

The approach to this study was experimental, and allowed an evaluation of the potential return on each of the three technical approaches. It consisted of selecting representative samples from each of the approaches and submerging them in the ocean. At regular intervals, the specimens would be retrieved from the ocean and their condition noted.

The scope of the study was limited in number of test specimens, AR coatings, alternate materials, plastic overlays, test conditions, and duration of submersion. As a result of this limitation, only the following potential approaches to increase the life of IR windows in an ocean environment were to be evaluated:

1. Alternate materials:
   a. Chalcogenide glass AMTIR-1
2. Competitive AR coatings for germanium:
   a. Single durable anti-reflective coating applied to germanium by Exotic Materials.
   b. Single anti-reflective coating applied to germanium by Optic Electronic.
3. Competitive plastic overlays for IR materials:
   a. Single-layer polyolefin (PO) coating applied to germanium by Lane Instrument.
   b. Multi-layer polyethylene/polypropylene (PE/PP) coating applied to germanium by Honeywell Inc.

In the selection of approaches to increasing the corrosion resistance, the length of submersion was limited to 4 months, the maximum duration of a submarine mission, while the ambient environment was limited to only two conditions: natural water circulation and forced water circulation, both performed at a depth of 35 feet. The natural circulation of seawater was to simulate the flow of water, encountered by the IR system in retracted position inside the sail of a submarine, while the forced circulation was to simulate the flow of seawater past the IR system when the sensor mast was either in a partially or fully extended position. In addition, electric potential was to be applied to some of the specimens so that the de-icing procedure for IR windows in polar regions could be adequately simulated.

It was thought that by comparing the extent of corrosion of the specimens after a 4-month submersion in an identical ambient ocean environment, an objective evaluation could be performed on the merits of the three different approaches to extending the life of IR windows in an ocean environment. It was hoped that there would be clear-cut evidence which would indicate that the potential return on research investment in one of the three approaches was superior to the two others, or at worse, that two of the approaches were superior to the third one.

In either case, the return on research investment would be increased by channeling it into one, or at most, two approaches rather than into three. If two approaches to the problem merited further research investment, they probably could be ranked according to the lead time required for providing successful solutions to the problem of seawater corrosion, and thus could be attacked sequentially instead of simultaneously. This certainly would allow focusing all of the available resources on one approach at a time. The first approach to be funded would be the one which would provide acceptable results in the shortest possible time, while the second approach to be funded would be the one which would provide optimum results, but only at some future date.

The selection of test specimens for this study was mainly based on the findings of an exploratory study conducted by NOSC in 50-foot depths from the NOSC offshore platform near Mission Beach, San Diego, California (reference 1). The findings of the preliminary study have shown that:

1. Surfaces of unprotected ZnSe windows deteriorate in seawater as rapidly as those of germanium windows.

2. AR coatings provide some protection to the surfaces of submerged germanium windows.

3. All wetted surfaces become organically fouled regardless of whether the surfaces are bare or AR-coated.

Thus, based on these findings, ZnSe was eliminated from consideration as a viable alternative to uncoated germanium, and further investigations into anti-fouling coatings for IR windows were abandoned as the potential return to research investment ratio in this area is very low. Instead, it was considered more profitable to investigate the fouling prevention technique which relies on a constant flow of water impinging upon the window face.

The experimental evaluation was initiated without any preconceived opinions on forthcoming results. There were, however, strong indications, based on personal communications with representatives of the IR research community and findings of the exploratory study conducted by NOSC, that the approach focusing on improved AR coatings for germanium would be rated the most likely to succeed in the near future if it were properly funded. There was indecision, however, on which of the two other approaches would be considered the long-range solution to the corrosion problem, since neither the plastic overlays nor the chalcogenide glasses had been previously considered for marine service; thus there was a total absence of data on which to base an opinion. It was hoped that there were sufficient test specimens and ambient test conditions to provide adequate findings on which the merits of the two competing approaches could be adequately differentiated. If this were the case, a comprehensive research plan could be developed which would define the steps to be taken in providing cost-effective, short-range and long-range solutions to the requirement for corrosion resistant windows in submarine-mounted IR electro-optical systems.

TEST PREPARATION

TEST SPECIMENS

All specimens tested were 3-inch-diameter, 1/4-inch-thick circular discs with polished faces (figure 1). There were 6 specimens of uncoated germanium, 37 specimens of germanium with various coatings, and 4 specimens of AMTIR-1 glass.

Those specimens which were used in the test fixtures utilizing electrical resistance heating had the coating on the dry face of the specimen (if any) sanded off in two spots 180 degrees apart along the circumference of the dry face. About a 1/4- by 1/4-inch area was sanded at each spot so that electrical contact could be made between the germanium and the electrical contacts of the test fixture. An inventory of the specimens used can be found in tables 1 through 4 of this report.

TEST FIXTURES

There were four test fixtures used in the experiment. One was a single-specimen fixture which utilized electrical current for heating of the specimens. The three other fixtures each held twelve specimens to be tested for fouling and corrosion under three primary conditions: with forced water circulation, without forced water circulation, and with electrical current heating.

The single-specimen test fixture was cylindrical, 4-3/8 inches long with a 5-7/8-inch diameter. It was constructed of polyvinyl chloride, with a hollow center to accommodate the electrical contacts and wires. One sectional surface of the cylinder had a recessed seat to hold the specimen so the sea-face of the specimen would be flush with the surface of the fixture (figure 2). The opposite cross-sectional surface of the cylinder held the electrical plug and the thermocouple lead for monitoring the specimen temperature.

The specimen to be tested was sealed watertight into the fixture by an O-ring under a titanium ring clamp which was held down by eight 3/4-inch stainless screws (figure 3). Electrical contact was made by helical springs placed in holes in the PVC seat of the specimen (figure 2). The springs were compressed by the specimen when it was sealed in, thus making electrical contact with the dry face of the specimen. When compressed, these springs also made contact with brass strips on a PVC base plate, which was wired to a watertight electrical plug in the bottom cylindrical section (figure 4). This plug was, in turn, plugged into a cable which conducted current to the fixture from a power supply located above the water's surface.

A thermocouple wire for the measurement of specimen temperature was threaded through a hole in the base of the fixture, which was then sealed watertight with a silicon rubber sealant (figure 4). This thermocouple probe was left loose in the cavity beneath the specimen (figure 2). It was subsequently affixed by a one-inch square of duct tape to the dry face of the specimen being tested.

The multiple-specimen test fixtures were labeled "A", "B", and "C", respectively for no forced circulation, forced circulation, and electrical current heating. The specimen holders for fixtures A and B were a PVC sheet, 21.00 × 16.00 × 1.00 inches. Each had twelve evenly spaced recesses for specimens, which after mounting, would be flush with the surface of the PVC plate. Each recess had a 1/4-inch-wide seat around the circumference that the specimen rested on, and a shallow cavity below the specimen. The specimen holders had evenly spaced holes in them to accommodate the PVC studs used for fixture assembly.

Each specimen was placed in the fixtures on a nylon-fiber-reinforced neoprene gasket that fit on the specimen seat. The specimen was then fastened watertight with an O-ring which was held down by a titanium ring clamp fastened with nylon screws (figure 5).

PVC studs were placed through the specimen holders and 3-inch tubular PVC spacers were placed over the studs (figure 6).

For fixture A, 1/2-inch-thick acrylic sheets were placed on either side of the specimen holder as a protective cover for the specimens. These were drilled in the same manner as the specimen holder so that the studs would pass through them. The acrylic sheets were fastened in place with 1/2-inch PVC washers and hex nuts (figure 7).

Fixture B had a similar protective acrylic sheet on the back side of the specimen holder, but the acrylic sheet over the specimens was fitted with a device to provide for forced circulation (figure 8). This device consisted of a Blue Cascade Submersible Pump, model B1 000, which circulated seawater through a manifold. The manifold was made of 1/2-inch copper pipe with brass fittings. The pipes passed through holes in the acrylic plate centered above each specimen. The manifold was secured to the acrylic sheet by fittings on the specimen side of the acrylic plate, which were nozzles that directed a stream of water on the specimens.

The arrangement of waterflow in the manifold, combined with various diameter apertures in pipe caps placed on the nozzles, provided for the adjustment of the twelve water jets to the desired water velocity of 6 feet per second. When the acrylic plate and manifold were placed over the studs, the tubular spacers provided a 3/4-inch standoff for the water nozzles above the specimens (figure 9). Both acrylic plates were secured to fixture B to complete the test fixture (figure 10).

The specimen holder for fixture C was also of PVC, having the same specimen and stud hole arrangement as fixtures A and B. Also, specimens were secured in the same manner as in fixtures A and B. For fixture C, however, the wells beneath the specimen seats were drilled all the way through, and the reverse side of the holder was channeled in order to connect these wells (figure 11). This was to facilitate application of a vacuum to the interior of the fixture.

The specimen holder in fixture C was backed by a second sheet of PVC of identical dimensions. Into this sheet a hole was drilled for a vacuum pump fitting. It was fitted with a plug to seal the hole. A similar hole had been drilled along the edge of the fixture. This hole was plugged and not used.

A plug with a two-prong electrical connection was fitted to a space along the edge of the fixture and connected to a printed circuit board. The printed circuit board (figure 12) was arranged so the specimens would be electrically connected in parallel. The circuit board was sandwiched between the specimen holder and the backing PVC plate (figure 13) and the edges between them were sealed with a rubber sealant (figure 14, top edge). The areas around the stud holes in both PVC plates were spotfaced and sealed with small O-rings (figure 13). PVC studs and hex nuts used to assemble the fixture were later replaced with stainless steel studs and nuts to ensure enough pressure between the specimen holder and the backup plate to adequately seal the O-rings.

Contact between the printed circuit board and the specimens was made by the compression of helical springs located between the specimens and the printed circuit board. These springs were inserted in slots in the PVC seat for each specimen. This method was also used for electrical contact in the single specimen test fixture.

All three multiple-specimen test fixtures were fitted with aluminum angle stands by which the fixtures could be attached to the testing platform with steel C-clamps.

TEST ARRANGEMENT

There were two main phases to the testing: the preliminary indoor testing with current heating and the primary fouling testing, which took place in San Diego Bay.

The indoor tests (in building 1, NOSC, Bayside), using the single-specimen test fixture, were performed in a container filled with seawater obtained from San Diego Bay. The test fixture was immersed, specimen end at the top facing the surface, and set upon a block stand in the water. The fixture's power cord and thermocouple wires for probes to indicate specimen and water temperature were brought out of the container to above-water instrumentation and power supplies. There were two power supply configurations for these tests, one direct current, the other alternating current (figure 15).

The primary fouling tests with the multiple-specimen test fixtures took place off Berthing Pier 160 using the Sonar Facility, located inside building 160B. This NOSC, Bayside building housed a hydraulically-operated hoist which lowered the specimens into San Diego Bay. The hoist had a flat platform to which the test fixtures could be attached. That platform was on a cart which moved along tracks set at a 30-degree inclination to the water's surface (figures 16 and 17). The cart was raised or lowered by means of cables on a rotating drum driven by a hydraulic motor (figure 18).

For the best utilization of available space, fixtures A and B were assembled with the specimen holders placed back to back (figure 19). These were secured to the hoist platform with C-clamps (figures 18 and 20). The power cable for the circulation pump was manually payed out along the cart track, and it was connected to the ac power line in building 160B.

When fixture C was operational it was placed on the platform opposite fixture A/B (figure 20). It was secured to the platform in the same manner as the other fixture.

When fixture C was no longer operational the single-specimen test fixture was attached to the hoist platform opposite fixture A/B, and it was used for the in-ocean current testing (figure 21). The fixture rested along its longitudinal axis on two joined pieces of angle iron. The fixture and stand were secured to the platform by a metal wrap clamp (figure 22). The fixture's power cable was manually payed out along with that of fixture B.

INSTRUMENTATION

In the series of indoor tests, temperature readings were taken from a Doric Thermocouple Indicator, DS-350 Type J. The two temperature probes were made from Serv-Rite Thermocouple and Extension Wire, ISA Type J, the ends of which were stripped and then coated with Polystyrene Q-Dope.

The dc indoor test was powered by two Power Designs, Inc.-regulated dc-power sources, model 5015T. These were wired in series to provide for 1/2 ampere maximum current. For the ac tests, a Powerstat Variable Auto Transformer, Type 116B with an adjustable output from 0 to 140 volts, was used. Current was manually limited at a maximum 1/2 ampere via the Powerstat. A 0- to 3-ampere ac Simpson ammeter was used to measure current through the fixture.

For the bay tests, the pump on fixture B was connected in series through a 0- to 10-ampere ac Simpson ammeter to the ac outlet in building 160B, rated at 20 amperes, 220-volts ac maximum. The initial pump voltage reading was taken with a Micronete FET-VOM model 22-206. Ocean temperature readings were taken with a mercury column thermometer, with a range of −15 to 65 degrees Celsius.

When fixture C was operational it was connected through another Simpson 0- to 10-amperes ac ammeter to the Powerstat used for the indoor tests. Current was manually regulated by varying transformer voltage. Later, the same transformer was used to power the single-specimen test fixture. In series with these was a Triplet ammeter, 0- to 500-milliamperes ac, off of which fixture current data was taken. Again, current was manually limited by means of the transformer.

TEST PROCEDURES

The indoor testing of the germanium specimens was an initial phase of current testing to observe which coatings would hold up the best when submitted to heating by electrical resistance.

As an initial test of the fixture and equipment, an uncoated germanium specimen was tested 2 June 1978. The current steady state was approximately 1/2 ampere at 60 volts ac. This test was run for approximately 10 minutes. Inspection of the housing showed no leaks or damage to the housing.

Seven specimens with various coatings were then tested in the fixture (table 1). Data which were taken at 15-minute intervals included the fixture potential and current, the specimen temperature and the water temperature. At the initiation of the test, and at 1-hour intervals thereafter, photographs were taken of the specimen, and a qualitative description of specimen condition was noted.

Table 1. Specimens tested in indoor current tests.

Specimen Number	Manufacturer	Coating: Sea face	Coating: Dry face	Date Tested
32	Exotic Materials	AR	No Coating	7-5-78
46	Exotic Materials	No Coating	No Coating	7-11-78
5H	Honeywell	3-layer AR PE/PP/PE	3-layer AR PE	7-7-78
12H	Honeywell	1-layer AR PE/PP/PE	1-layer AR PE	7-12-78
13H	Honeywell	AR, Tenite	AR	7-14-78
1	Lane Instrument	PO	No Coating	7-10-78
20	Optic Electronic	AR	AR	6-30-78

Tests were from 4 to 8 hours in duration, depending upon the condition of the specimen. Only one specimen was tested using direct current, as it was noted that the use of direct current caused pitting of the specimen directly over the anode. The remainder of the specimens were tested with alternating current, which lessened the amount of severe localized pitting on the specimens above the electrodes. (See "Findings" for more details.)

For two of the multiple test fixtures, A and B, two specimens each from the four manufacturers were used in each specimen holder. In addition, each fixture held two uncoated germanium specimens and two specimens of AMTIR-1 glass.

The specimens in fixtures A and B, listed in tables 2 and 3, respectively, were arranged in the fixtures for data collection (figures 23 and 24 show arrangement).

The combined fixture of A and B was lowered into the bay and the testing commenced 22 July 1978. Data from each specimen were recorded, including day of the test, and qualitative visual observations of growth on, and physical condition of, the specimen. Also noted for fixture B were the current that the pump was drawing and whether water was flowing from the manifold. Further, the data included a description of ocean conditions such as the water temperature, tide-induced water circulation, the water surface conditions, and the sunlight conditions.

For approximately the first month of testing, data were taken daily and the test fixtures were brought out of the water on weekends to assure that the manifold apparatus on fixture B was operating correctly. The pump had failed on the seventh day of the test and it was determined that the impeller had not been correctly affixed to the driving shaft by the manufacturer. As such, the impeller had come loose and was driven into the intake housing. The pump was repaired with the damaged impeller left in place and operated at a reduced flow rate for five days until a replacement impeller was obtained and installed.

Table 2. Specimens used in fixture A: no forced circulation.

Specimen Number	Manufacturer	Coating: Sea face	Coating: Dry face	Notes
54	AMTIR (glass)	No Coating	No Coating	
55	AMTIR (glass)	No Coating	No Coating	
34	Exotic Materials	AR	No Coating	
35	Exotic Materials	AR	No Coating	
47	Exotic Materials	No Coating	No Coating	
48	Exotic Materials	No Coating	No Coating	
2H	Honeywell	3-layer AR PE/PP/PE	3-layer AR PE/PP/PE	Transmission measured
8H	Honeywell	1-layer AR PE/PP/PE	1-layer AR PE	Transmission measured
2	Lane Instrument	PO	No Coating	
3	Lane Instrument	PO	No Coating	
11	Optic Electronic	AR	AR	
12	Optic Electronic	AR	AR	

Table 3. Specimens used in fixture B: forced circulation.

Specimen Number	Manufacturer	Coating		Notes
		Sea Face	Dry Face	
56	AMTIR (glass)	No Coating	No Coating	
57	AMTIR (glass)	No Coating	No Coating	
36	Exotic Materials	AR	No Coating	
37	Exotic Materials	AR	No Coating	
49	Exotic Materials	No Coating	No Coating	
50	Exotic Materials	No Coating	No Coating	
4H	Honeywell	3-layer AR PE/PP/PE	3-layer AR PE	Transmission measured
9H	Honeywell	1-layer AR PE/PP/PE	1-layer AR PE	
4	Lane Instrument	PO	No Coating	
5	Lane Instrument	PO	No Coating	
13	Optic Electronic	AR	AR	
14	Optic Electronic	AR	AR	

On 8 September 1978, it was decided that the test fixtures would be left in the water continuously with the exception of raising the apparatus three to four times a week for inspection of specimens. It was felt that this would most closely approximate actual periscope conditions for fouling.

Photographic documentation of the specimens' surfaces in fixtures A and B was taken before testing was initiated (figures 23 and 24), and after the first, second, and fourth or final months of testing.

Throughout this period, fixture C (figure 25) was in the process of assembly and vacuum testing for watertightness. The design was modified slightly and the fixture was resealed several times until it was watertight. It was taken to the test site on 11 August 1978 and affixed to the hoist for testing. Data taken included the day of the test, visual observations, and ocean conditions in a format identical to the information taken for fixtures A and B. Also recorded were the potential across, and current through, the fixture. For initial testing the fixture was lowered to 2 feet below the surface. Approximately 50 volts ac were applied to maintain a reading of 6 amperes total on the fixture, which would apply 1/2 ampere to each specimen. Periodic adjustments were made in the voltage to obtain a steady-state current.

After 20 minutes of testing, the fixture was brought up for data collection. It was discovered that several of the specimens had pitted, and that one had drawn enough current to char and melt the PVC socket which that specimen fit into. This temporarily halted the testing.

From 15 through 22 August 1978, the fixture was disassembled, cleaned, and the six specimens which sustained the most severe damage were removed from electrical contact

with the circuit. The specimens were photographed to document damage, and were re-arranged for ease of data taking (figure 26). The fixture was again sealed and vacuum tested.

On 23 August 1978, the fixture was again lowered into the water. A current of 3 amperes was maintained on the fixture to provide 1/2 ampere on each specimen. It was necessary to apply 80 to 100 volts ac across the fixture to maintain the correct current. After 5 minutes of testing, the fixture was raised and it was noted that some specimens had begun to decay.

The fixture was again lowered and 70 to 80 volts ac were applied to maintain 3 amperes for an additional 15 minutes of testing. When the fixture was raised additional damage to the specimens was noted; thus testing with fixture C was discontinued. The condition of the specimens was again documented photographically.

Because the results of current testing with fixture C indicated that this multiple-specimen test fixture could not assure an equal amount of current through each specimen without major design revisions (i.e., a current-regulating device would have to be designed and fabricated for each specimen), it was decided to current-test the remaining specimens with the single-specimen test fixture that had been used for the indoor testing.

Three specimens were tested in the single-specimen fixture (table 4), with a maximum of 50 volts ac to maintain 1/2 ampere of current. The testing of each specimen was continued until that specimen was notably pitted (usually by corrosion). The test longest in duration was that of specimen 27, which lasted 90 minutes.

Testing with this fixture was halted 22 September 1978, when at approximately 15 minutes into the third test a dead short was noted on the current meter. Upon raising the fixture the cause of the short was found to be that the specimen being tested, 14H, had shattered. The resultant damage to the fixture from the short rendered it unsuitable for further use.

The testing of specimens in fixtures A and B was discontinued after approximately 4 months of testing, on 11 December 1978.

Table 4. Specimens tested in the single specimen fixture in San Diego Bay.

Specimen Number	Manufacturer	Coating		Date Tested
		Sea Face	Dry Face	
14H	Honeywell	AR, Tenite	AR	9-22-78
23	Honeywell	PE	No Coating	9-13-78
27	Honeywell	PE	No Coating	9-20-78

FINDINGS

GENERAL OBSERVATIONS

All test specimens were periodically removed from the bay, photographed, and subjected to minute visual inspections. The inspections focused on the degree of fouling, depth of corrosion pits, and condition of plastic coatings. During these inspections the specimens were not removed from their mountings, nor their surfaces cleaned. Only after conclusion of all the testing in the bay (approximately 4 months of exposure to sea environment at a 35-foot depth) were the surfaces of all specimens thoroughly cleaned to prepare them for IR transmission measurements.

No Electric Current, Natural Circulation (Tidal currents with 0.5 knot peak velocity)

After the first month of testing, all specimens showed signs of a growth film and some fine spotting. By 2 months the amount of growth had visibly increased, and included minute worms along with the spotting growth, and a small barnacle (figure 27). The growths showed no apparent preference for any particular type of coating, but rather were dispersed about the specimens in the fixture.

At tests' conclusion the growth on the specimens had increased considerably (figure 28). By that time, life forms included worms up to approximately 1-1/2 inches long, acorn barnacles up to 1/2 inch diameter, small shrimp, growths of coral up to 1-1/2 inches diameter and an increased amount of spotting and slime.

Of the coated germanium specimens, those having the Exotic Materials anti-reflection coating were in the best condition after the first month of testing, showing no physical defects (figure 29). There were still no defects visible after the second month of testing. At the conclusion of testing, the specimens had begun to show some pinpoint pitting (figure 30), but damage was superficial.

The specimens with the anti-reflection coating from Optic Electronic were the only coated specimens to begin to corrode within the first month of testing. Superficial pinpoint size pitting was dispersed across the surfaces of the specimens (figure 31). This pitting more than doubled in density by the second month of testing, and again noticeably increased in both density and in size of individual pits by the final month of testing. The pits ranged from very fine to 1/10 inch diameter, and were all less than 1/32 inch deep (figure 32).

The two plastic coatings showed no signs of tearing or pitting throughout the experiment, but one of the plastic coatings had problems with adhesion to the anti-reflection layer within the first month.

The Honeywell coating of polyethylene/polypropylene/polyethylene began to discolor within the first weeks of testing. By the end of the month, about 90 percent of the surface of each specimen was affected (figure 33). The Honeywell specimens continued to discolor and wrinkle somewhat in the following months, but the coatings did not significantly peel away from the specimens by the conclusion of the test (figure 34).

Within the first week of testing the polyolefin polymer coating of the Lane Instrument specimens had begun to bubble up. At the end of 1 month of testing (figure 35), one-quarter of the coating was loose from the surface. The coatings continued to peel away from the specimens' surfaces, though at a much slower rate, until the conclusion of the test (figure 36). Throughout the test, the coatings showed no holes or cracks, and there was no visible pitting of the specimens.

The uncoated germanium specimens showed no pitting throughout the testing period. By the first month some discoloration was apparent (figure 37), and the surface became superficially etched in appearance by the end of the testing (figure 38). Approximately 0.0017 inch was etched away during the 4-month period.

The only non-germanium specimens, the chalcogenide germanium glass AMTIR-1, showed no corrosion or change of physical condition throughout the testing period (figures 39 and 40).

The condition of all the specimens after organic growth had been scrubbed off can be seen in figure 41.

No Electric Current, Forced Circulation (Impinging stream of water with 6 feet per second velocity)

With the exception of colonies of worms that lodged under the torn plastic coatings, and a few minute barnacles, the specimens in this fixture were relatively free of major growths through the duration of the test. There were growths on the fixture, as on the fixture without forced circulation, but the specimens themselves sustained less surface growth (figures 42 and 43).

The only germanium specimens to show no damage by pitting or coating decay by the end of the first month were those with the anti-reflection coating by Exotic Materials (figure 44). These specimens remained unpitted through the complete test (figure 45), showing only minor discoloration at the center. The discoloration of the center was apparently a direct result of the induced flow.

The anti-reflection coated Optic Electronic specimens exhibited pinpoint pitting within one week of testing initiation, and by the end of 1 month, the specimens had pitting dispersed across their surfaces, with the heaviest concentration at the centers (figure 46). The pits were a maximum of 1/16 inch diameter and 1/64 inch deep. The pitting increased in size and density in the next months and by the completion of testing (figure 47) the specimens were pitted solidly over 90 percent of their surface area, and no coating was left attached. The deepset pits were approximately 1/32 inch deep.

Both types of plastic coatings exhibited decay within the first month of testing. The Honeywell specimens (figure 48) had bubbled up around the edges, and by the second month a colony of worms had lodged between the coating and the surface of one specimen. This colony had grown larger by the end of testing (figure 49), and the specimen was found to have etching and pinpoint pitting on the surface under the peeled coating. Also, the dryface coating had completely peeled off due to water seepage.

The Lane Instrument coatings had cracked and torn as well as peeled up by the first month (figure 50). These coatings gradually discolored and further peeled away such that by the conclusion of the test (figure 51), one of the coatings had almost entirely peeled away from the surface. In addition, the surface was etched and had growth on it under the coating.

No pitting occurred on the uncoated germanium specimens during the testing period. The specimens had begun to discolor by 1 month (figure 52), and within the next month fine lines of etching were apparent on the surface. At the conclusion of the test this etching was still very superficial (figure 53), although it had increased. It was evenly dispersed across the entire surface.

As in the case without forced circulation, the AMTIR glass specimens sustained no damage (figures 54 and 55), and when cleaned showed only minor scratches most likely sustained during cleaning operation.

The condition of the specimens after organic growth had been removed may be seen in figure 56.

With Electric Current, Natural Circulation

In the indoor electric current tests an uncoated specimen, specimens with the Optic Electronic anti-reflection coating, and the Exotic Materials anti-reflection coating began to corrode within approximately 15 minutes of testing. All were tested for 4 hours and showed similar patterns of pitting and corrosion concentrated over the electrodes (figures 57, 58, and 59).

The specimens with the Lane Instrument polyolefin polymer layer over the AR coating, and those with the Honeywell polyethylene/polypropylene/polyethylene layers over the AR coating, sustained no damage during indoor testing. Thus, only specimens with these coatings were used in the tests in the bay.

After 20 minutes of testing in fixture C in the bay, the Lane Instrument specimens were pitted and had some areas of corrosion up to 1/8 inch diameter (figure 60). One specimen sustained a 1/4- by 1/6-inch pit on the sea-face over the electrode.

The Honeywell specimens sustained less damage (figure 61). The most severely damaged of these specimens had approximately one dozen pinpoint size pits.

After an additional 40 minutes of testing, the Honeywell specimens sustained further pitting and corrosion (figure 62). The most severe sea-face corrosion was a 1/8 inch-diameter pit in an area of corrosion about 1-1/8 inches in diameter. Another specimen was charred on the dry face by excessive current to the electrodes (see procedure for details of the circuit). Testing with this fixture was discontinued.

Three more Honeywell specimens were tested individually. Two were tested for approximately 90 minutes maximum, and both sustained corrosion, with deeper pitting at the center (figure 63). The third specimen shattered in the fixture after 15 minutes of testing. The specimen had no visible flaws prior to testing and the cause of the shattering is unclear.

TRANSMISSION MEASUREMENTS

Transmission tests were performed on all the specimens to compare the effectiveness of various coatings prior to, and after submersion in seawater. Both measurements were performed on specimens whose surfaces were cleaned and dried. These measurements only provide data on the transmission of electromagnetic radiation in the 6.5- to 13-micron wavelength range. The effect of surface deterioration on the MTF (mean transfer function) of specimens was not measured. Thus it is not known how much the optical resolution of a thermal imaging system would suffer were it equipped with windows coated in the same manner as the test specimens exposed to seawater environment.

Bare AR Coatings

The AR coatings from Exotic Materials, Optic Electronic and Honeywell were tested for percentage of transmittance of light in the spectral range of approximately 7 to 13 microns. It should be noted that the Optic Electronic and Honeywell specimens were coated on both sides, whereas the Exotic Materials specimens were coated on only one side.

Prior to saltwater exposure, the Optic Electronic coating transmittance plotted as a smooth curve, peaking reasonably flat between 9.5 and 10.5 microns at 97 percent transmittance (figure 64).

The Exotic Materials specimen exhibited a curve (figure 65) which was flatter than the Optic Electronic curve, varying only 10 percent from 7 to 13 microns, as contrasted with an approximate 30-percent variation of the Optic Electronic curve within that wavelength range. The Exotic Materials curve peaked lower, at 64-percent transmittance, between 8.5 and 10.5 microns, but it must again be emphasized that this is a predictable result because the specimen was coated on only one side. Coating on both sides would raise the figure for maximum transmittance.

For the Honeywell AR coating, the peak was shifted to a slightly lower wavelength, being reasonably flat at 96-percent transmittance between 8.9 and 9.7 microns (figure 66). Also, the roll-off from peak transmittance to values for higher wavelengths was steeper than either of the other specimens.

After exposure to salt water the Exotic Materials specimens exhibited a transmission curve which had retained its shape but shifted to a value 1 to 5 percent lower in transmittance (figure 65). The Optic Electronic curve, however, changed noticeably (figure 64), with the peak transmittance shifting to 89-percent transmittance between 8.0 and 8.5 microns. The curve dropped from there, showing a drop in transmittance of approximately 22 percent from the pre-exposure peak at 10 microns. Results of saltwater testing are not available for any of the Honeywell specimens as none of the Honeywell coatings withstood seawater exposure well enough to be retested for transmissivity.

Plastic Overlays

The plastic overlays which were tested over AR coatings — the Lane Instrument polyolefin polymer and the Honeywell combinations of polyethylene/polypropylene/polyethylene and Tenite — all reduced the level of transmittance of the AR-coated specimens.

The transmissivity curve of the Lane Instrument overlay had some inaccuracies at either end of the 7- to 13-micron range, but at midrange the slope of the transmissivity curve prior to application of the polyolefin overlay was reasonably maintained (figure 67). In this area transmittance was decreased approximately 20 to 25 percent by application of the polyolefin overlay on the Exotic Materials AR coating on a surface of the test specimens.

Of the Honeywell combinations of overlays, the specimen with Tenite on the sea face had the smallest reduction in transmissivity over the midranges, followed by the specimen with PE/PP/PE layers on the sea face and a polyethylene layer on the dry face. The specimen with the greatest reduction in transmissivity had the PE/PP/PE overlay on both sides (figure 66). Further, the curves for the overlay combinations which showed progressively greater reduction of transmittance were respectively less smooth, having a number of crests and troughs throughout the midrances of wavelength. Again, none of the plastic overlays resisted saltwater exposure well enough to allow testing for transmission after exposure to seawater.

Uncoated Materials

The transmittance of 0.25-inch-thick germanium specimens with polished surfaces prior to seawater exposure was approximately 49 percent in the 6- to 11-micron wavelength range. After exposure of one face of the specimen to a seawater environment for 4 months, the transmission through the specimen decreased by approximately 100 percent over the whole transmission range (figure 68). The dramatic decrease in transmission was caused by combined action of surface etching and oxidation.

The transmittance of 0.25-inch-thick chalcogenide glass AMTIR-1 with polished surfaces prior to seawater exposure was approximately 58 percent in the 6- to 11-micron wavelength range. After one face of the specimen was exposed to a seawater environment for 4 months the transmission through the specimen was virtually the same as prior to seawater exposure (figure 69). The absence of transmission loss after seawater exposure can be explained by the fact that the exposed specimen surface did not suffer any deterioration during its exposure to seawater.

CONCLUSIONS

1. Of the bare anti-reflection coatings, the Exotic Materials single-layer AR coating showed the best results. This coating had the flattest transmittance versus wavelength curve over the 7- to 13-micron spectral range, and it had the least drop in transmissivity after exposure to seawater. Of all the coatings tested by exposure to seawater, this coating degraded the least. Its decrease at a wavelength of 10 microns, was only 5 percent after 4 months of exposure to seawater.

2. The plastic overlay of polyethelene/polypropylene/polyethylene and of polyolefin polymer, did not offer the hypothetical added protection to the AR coatings. To the contrary, the plastic overlays degraded more rapidly than some of the bare AR coatings, and had the additional shortcoming of reducing the initial transmissivity of the specimens.

3. Forced circulation had the intended effect of decreasing the amount of growth on the surface of the specimens. However, the forced circulation also led to a more rapid decay of some of the specimens' coatings and surfaces (figure 70), though the coatings of other specimens did not show a noticeable difference (figure 71). Further testing would have to take place to determine whether the damaging effects could be minimized through changes such as altering the flow rate, while maintaining the benefit of hindering the marine growth.

4. The use of electric current in heating is not feasible without further testing and/or modification in method of application of current; as in these tests, electric current generally caused a rapid and uneven decay of specimen surfaces and was difficult to regulate.

5. The unprotected germanium surfaces corroded very uniformly during exposure to seawater at a rate of approximately 0.005 inch/year. The associated loss in transmission was close to 100 percent.

6. The unprotected chalcogenide AMTIR-1 glass surfaces showed excellent resistance to seawater corrosion, with no measurable loss of transmission during the 4-month exposure to seawater.

RECOMMENDATIONS

TECHNICAL

1. Germanium windows and lenses with unprotected surfaces should not be exposed to seawater environment as the etching of the wetted surface will decrease the transmission of signals in the 6 to 14 micron wavelength range to virtually zero.

2. Durable single, or multi-layer AR coatings show greater promise for protection of polished germanium surfaces against corrosion by seawater than thin layers of plastic, which in addition somewhat decrease the transmission of signals through the window.

3. The protected single-layer AR coating Exotic Materials No. 40104 can provide adequate protection for up to 4 months of submersion in seawater. Durable multi-layer AR coatings have the potential of increasing the protection to 12 months.

4. Chalcogenide glass AMTIR-1 windows and lenses with unprotected surfaces should be employed without any coating on the wetted surface since the bare surface resists seawater corrosion more effectively than any known AR coating. The transmission through an AMTIR-1 window with bare wetted surface is not decreased by 4 months of submersion, and it appears that there will be no significant decrease even when the duration of submersion is extended to 12 months.

ADMINISTRATIVE

5. Lenses and windows in IR receivers and transmitters wetted by seawater should be fabricated from either:

a. Optical grade germanium coated on the dry face with high efficiency broadband, and on the wetted face with durable broadband IR anti-reflective coatings, or

b. Optical grade chalcogenide AMTIR-1 glass coated only on the dry face with high efficiency, broadband IR anti-reflective coating.

REFERENCES

1. Naval Ocean Systems Center Technical Note 121, "Undersea Testing of IR Antireflective Coatings and IR Materials," by JN Ferrer, March 1977.

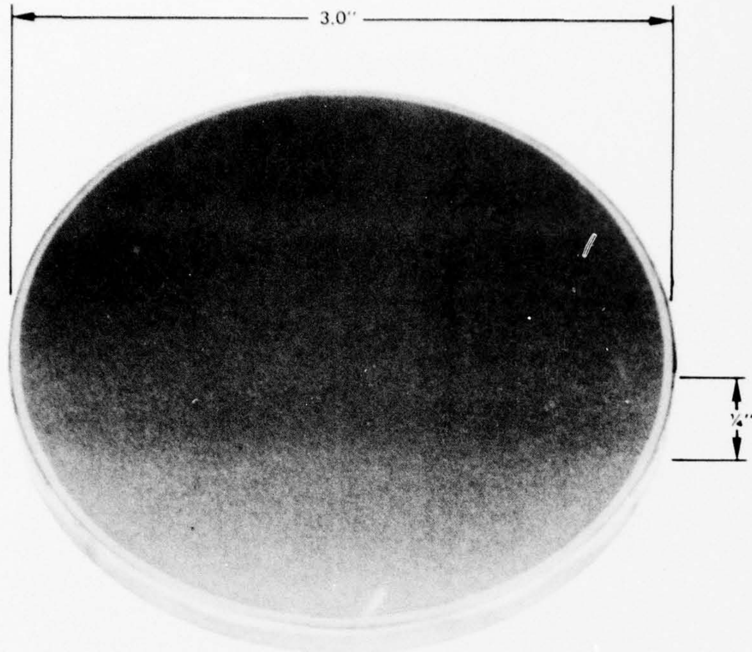


Figure 1. Typical specimen: this one is coated, showing face exposed to water.

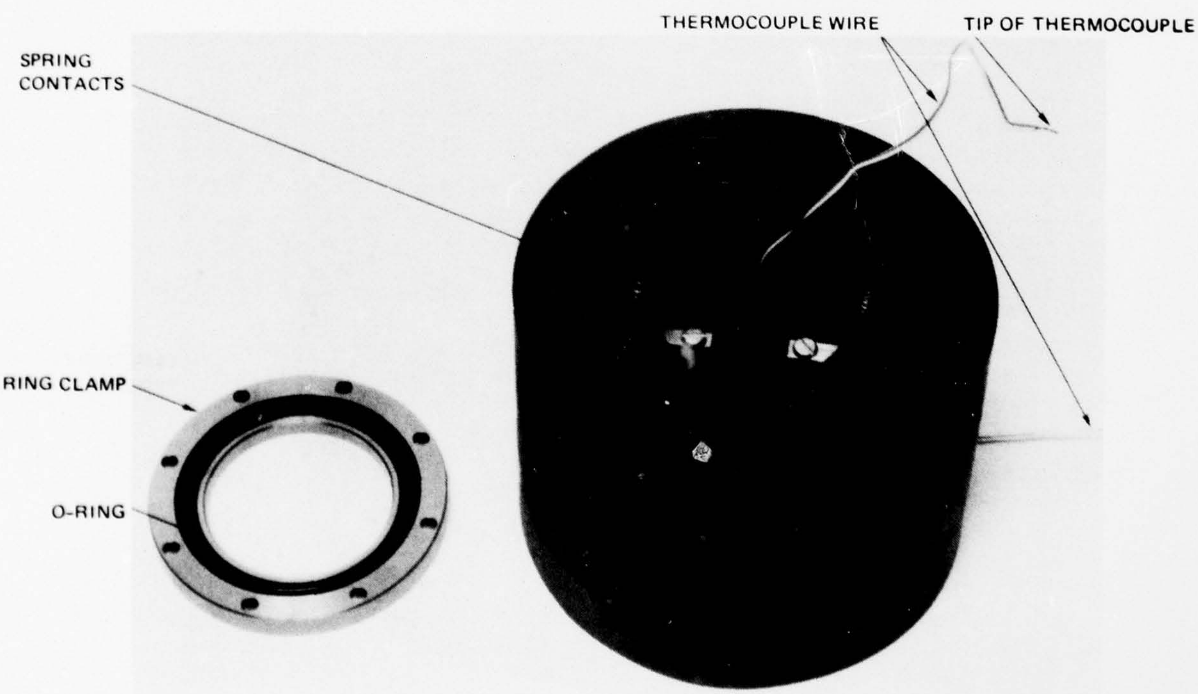


Figure 2. Single specimen fixture opened for placement of specimen.

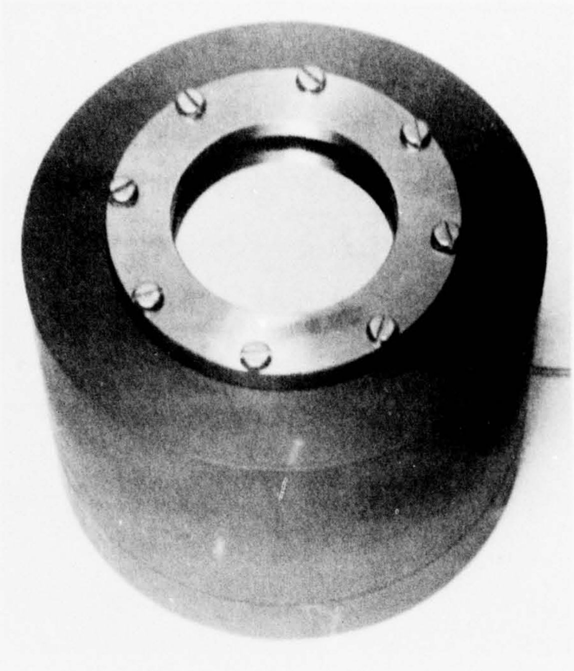


Figure 3. Specimen sealed in place.

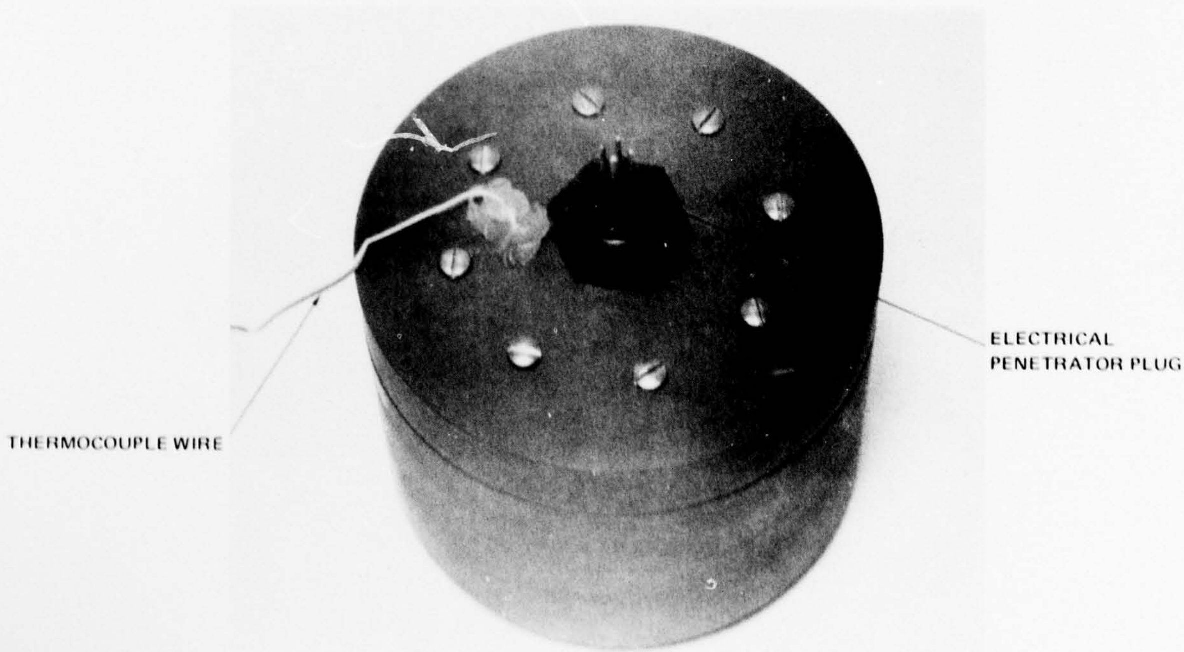


Figure 4. Detail of underside on single specimen fixture.

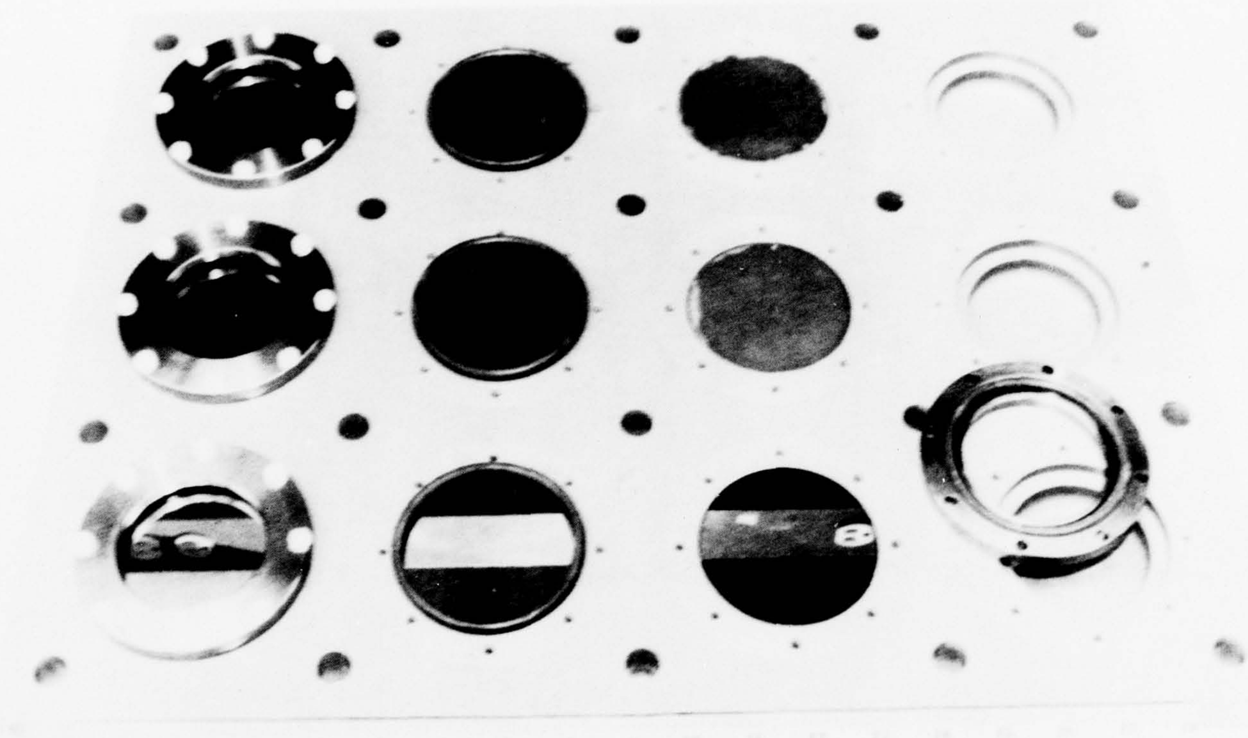


Figure 5. Multiple specimen fixture A in process of assembly.

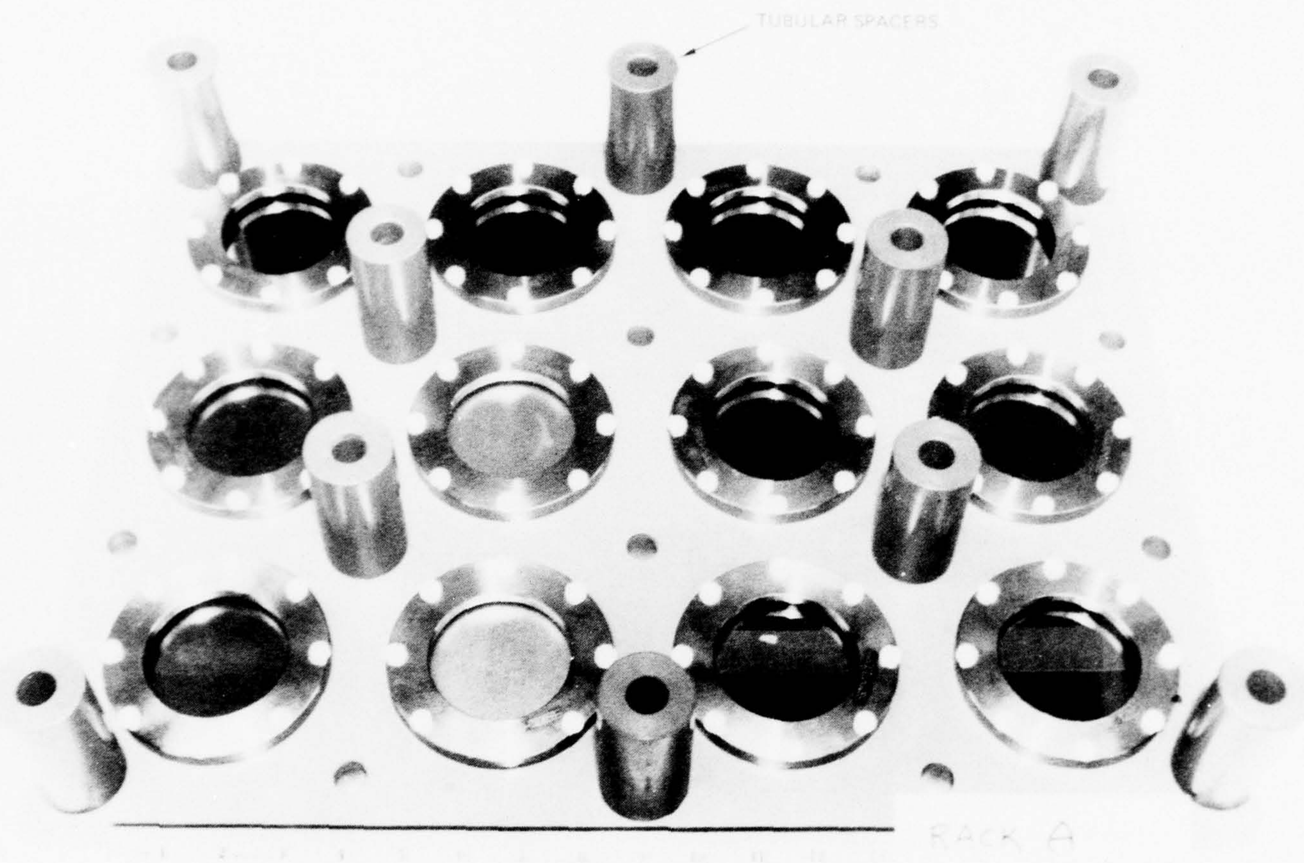


Figure 6. Multiple specimen fixture A in process of assembly, showing tubular spacers through which connecting studs pass.

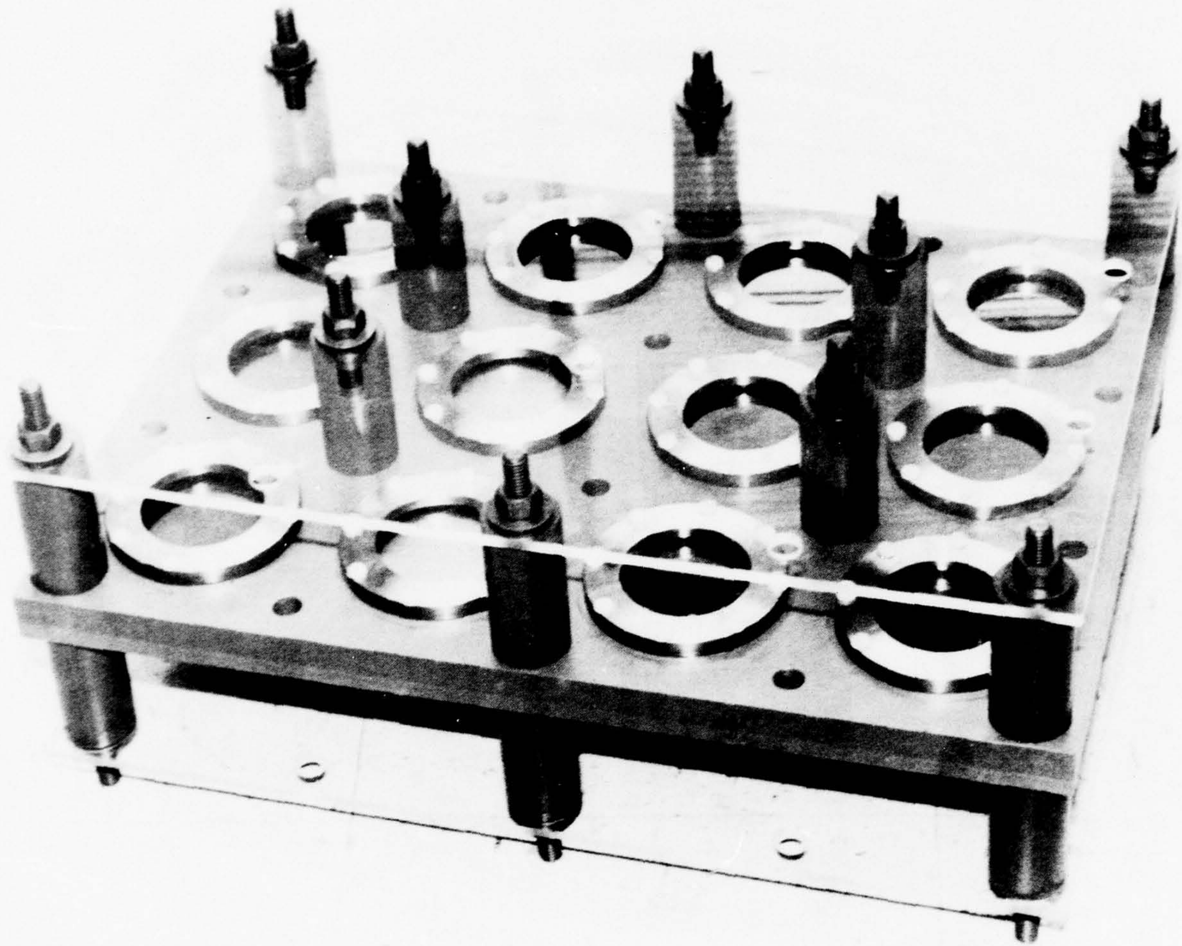


Figure 7. Completed test fixture A, showing protective acrylic plates.

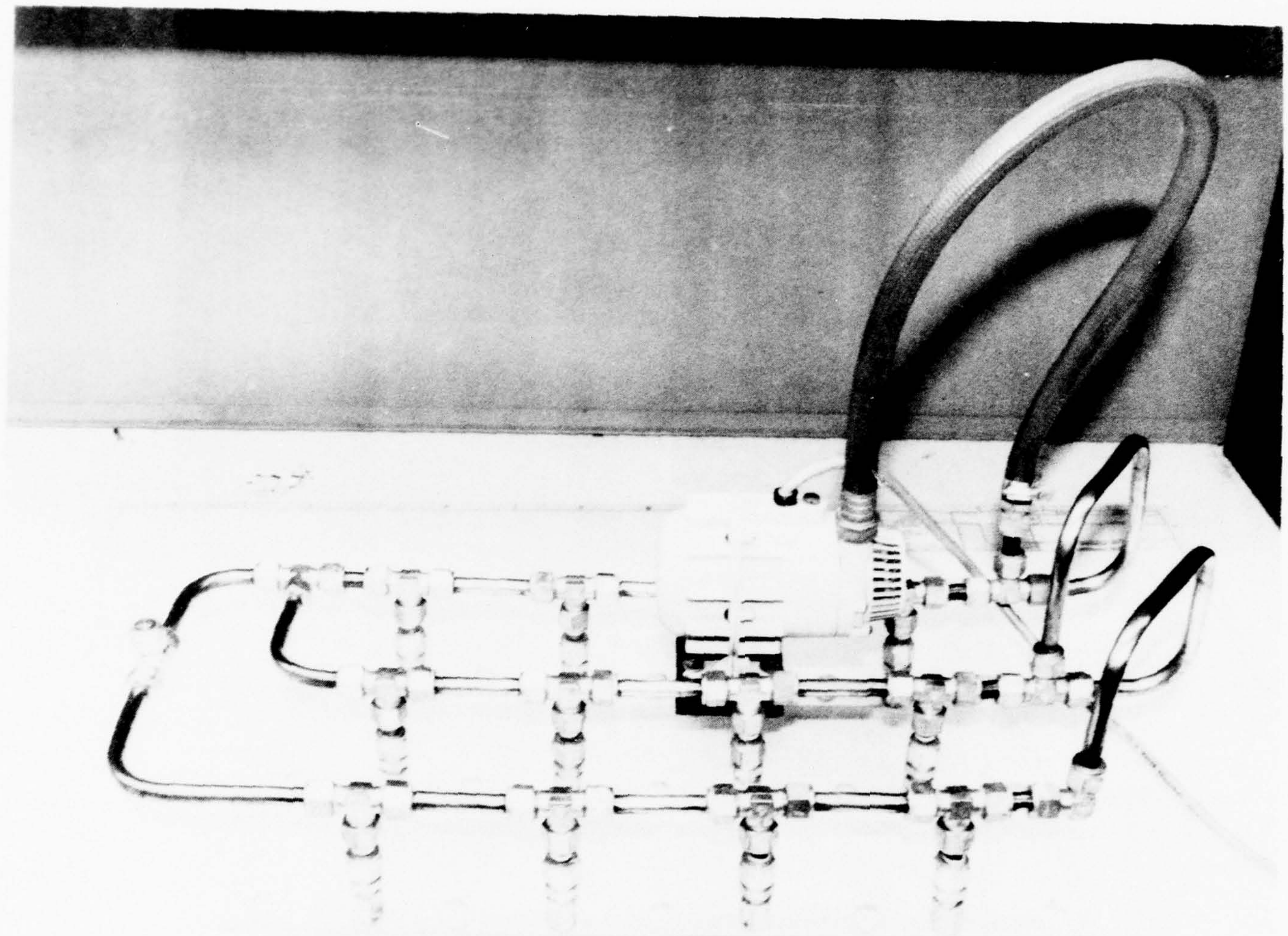


Figure 8. Manifold and pump for forced circulation, fixture B.

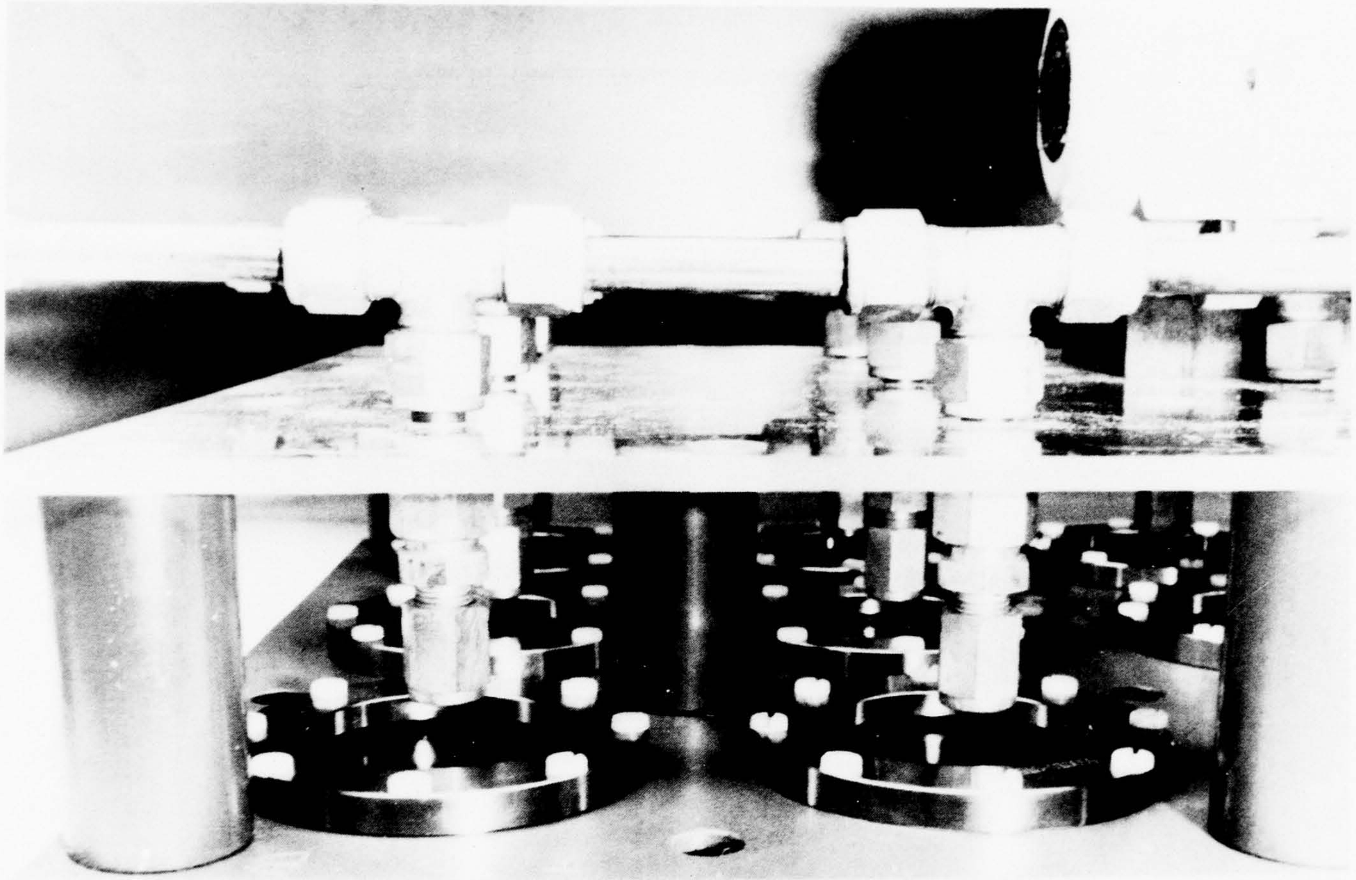


Figure 9. Placement of forced circulation nozzles over specimen fixture B.

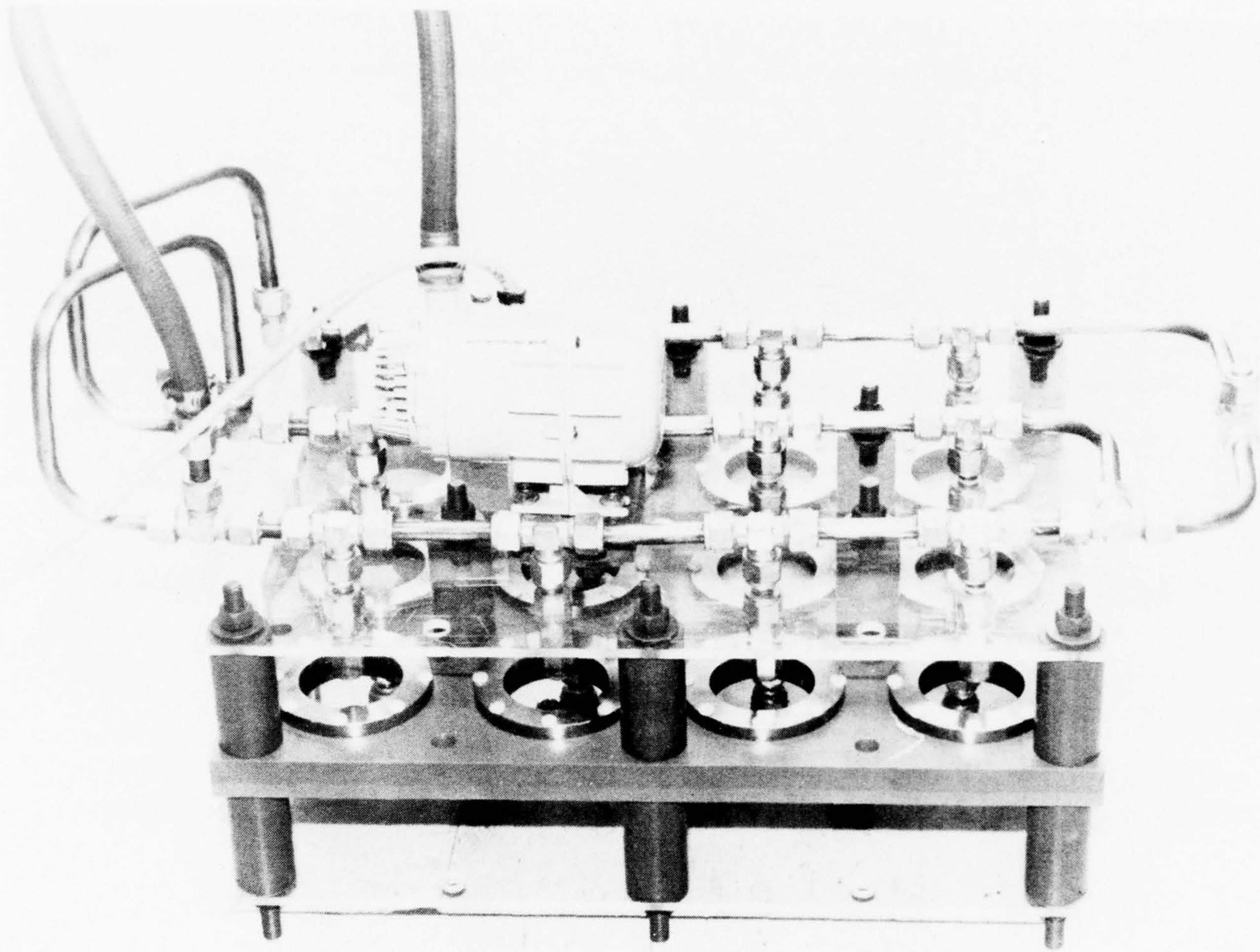


Figure 10. Complete fixture B, with forced circulation apparatus.

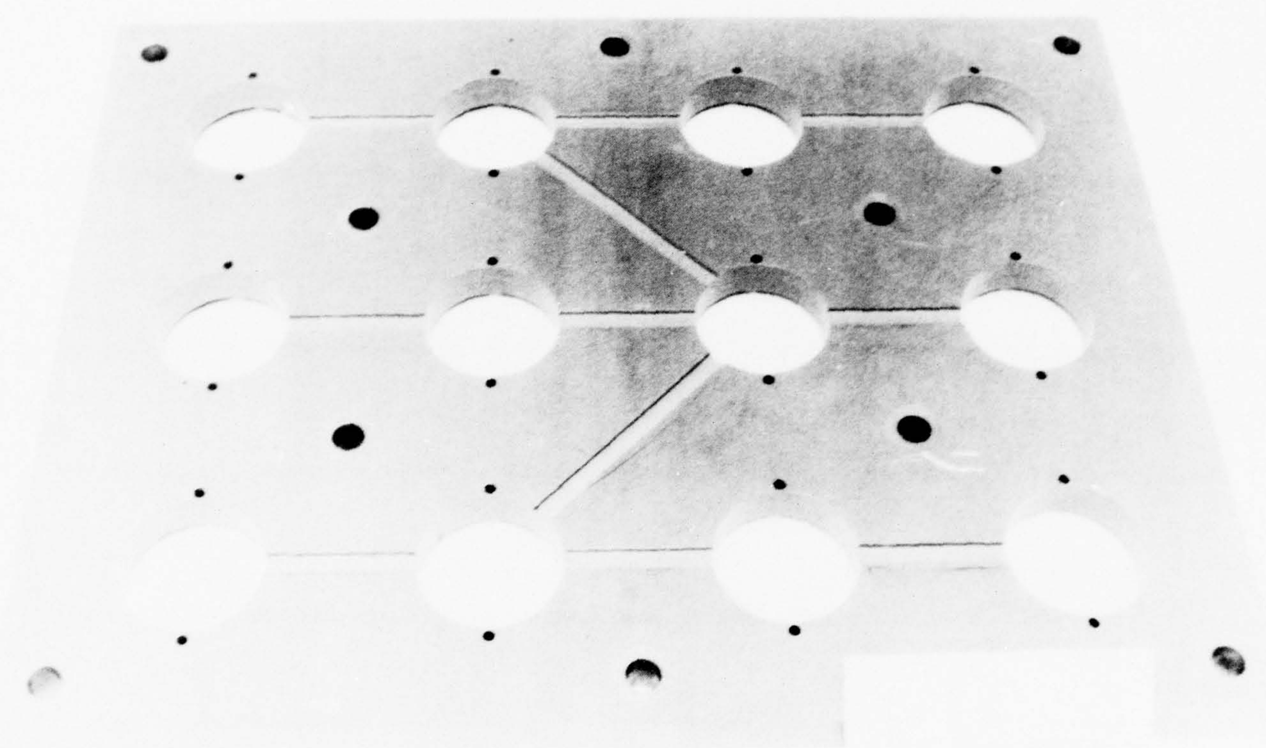


Figure 11. Specimen holder C, reverse side, showing channels for application of vacuum to the backside of specimens.

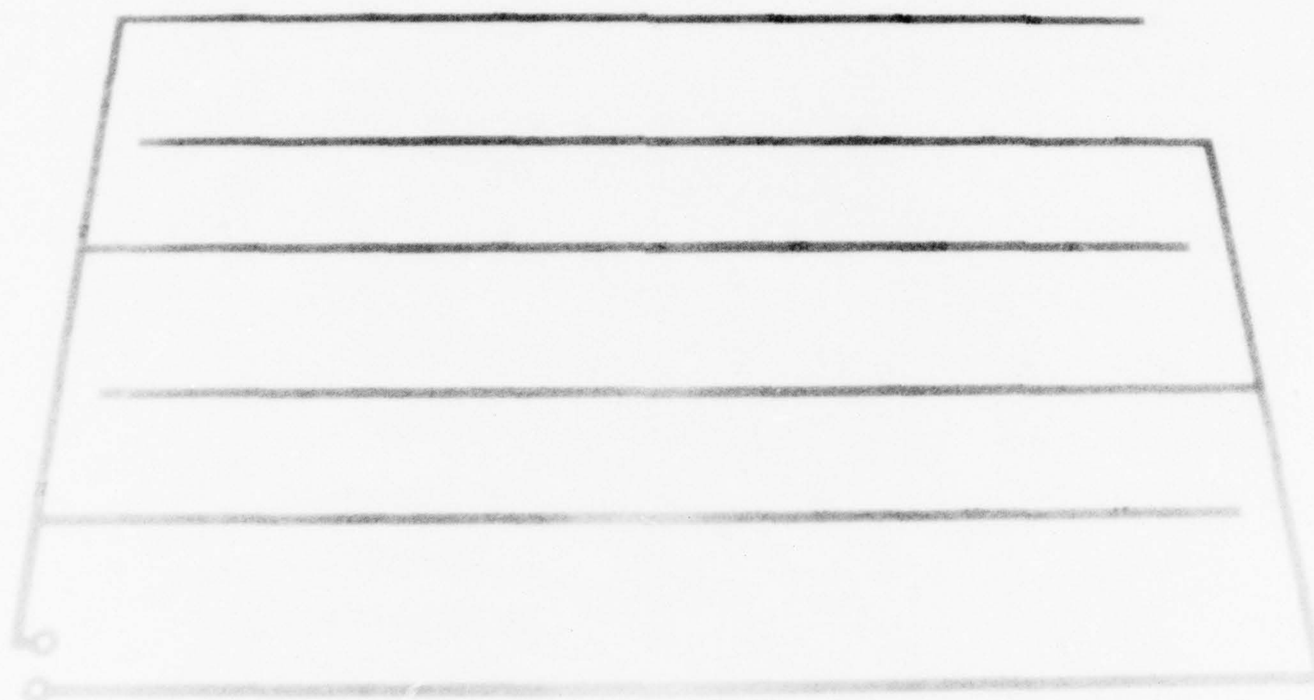


Figure 12. Printed circuit board for fixture C.

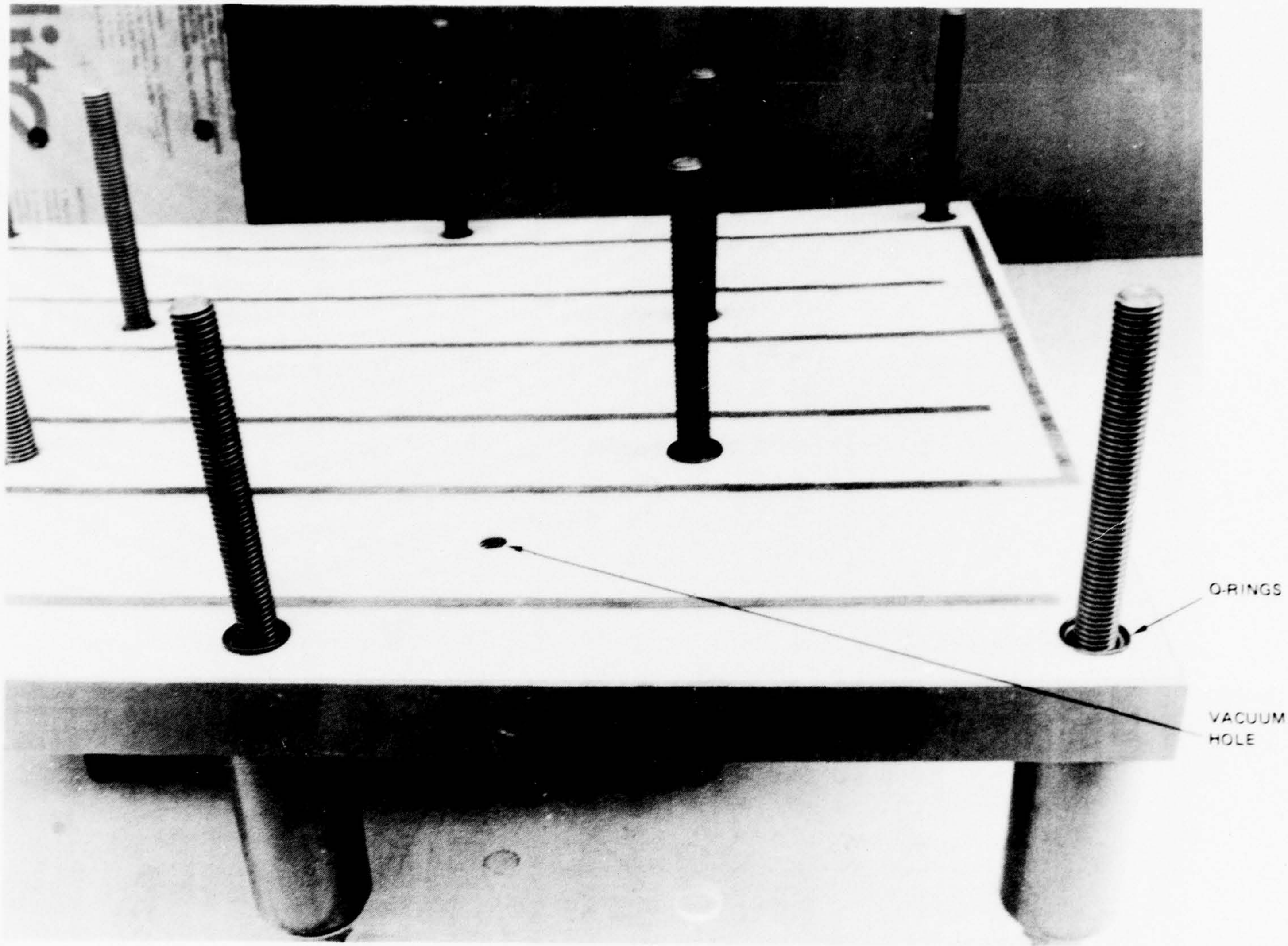


Figure 13. Fixture C in process of assembly, showing rear acrylic cover, PVC backing plate, printed circuit board in place and O-ring seals around studs.

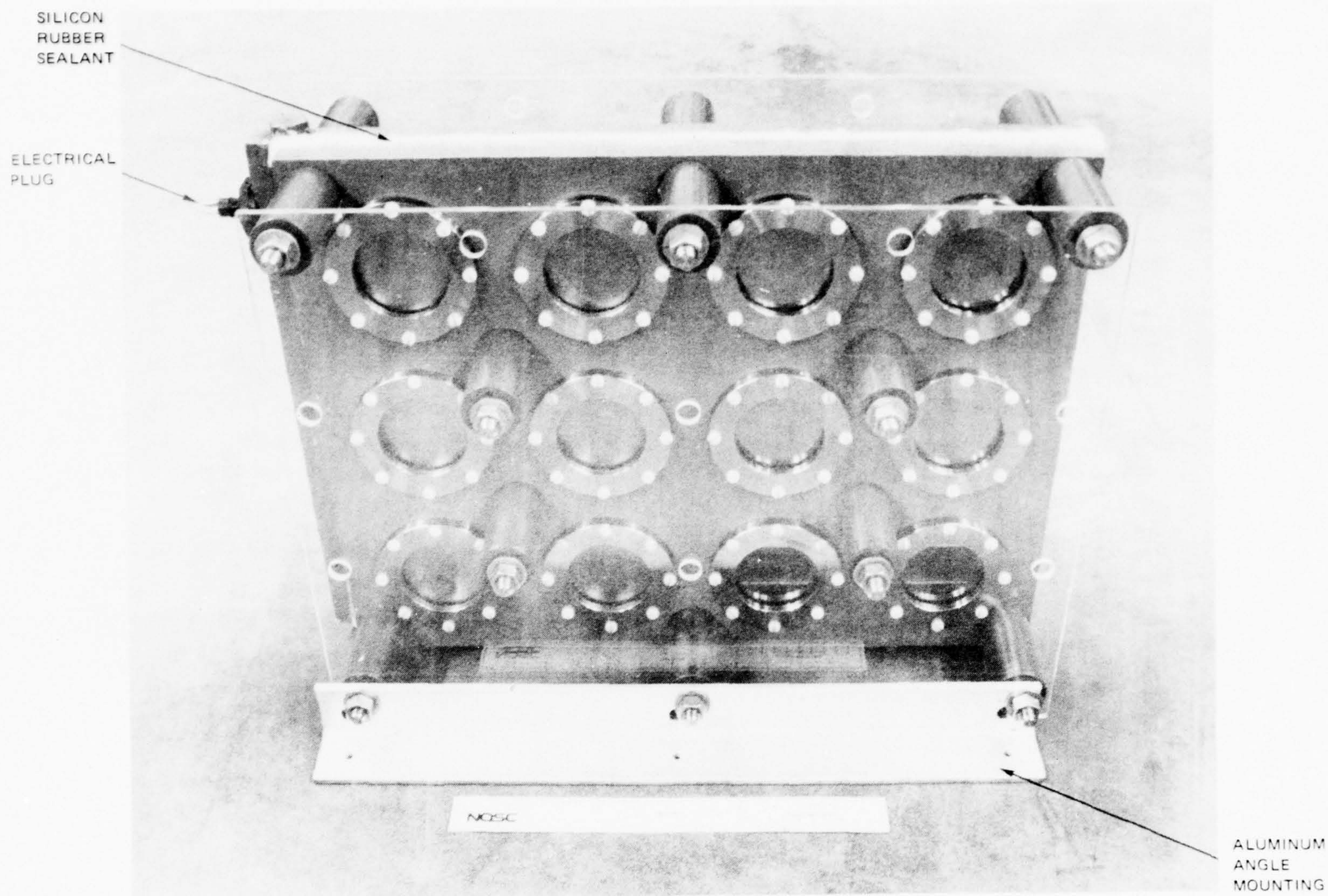


Figure 14. Completed fixture C.

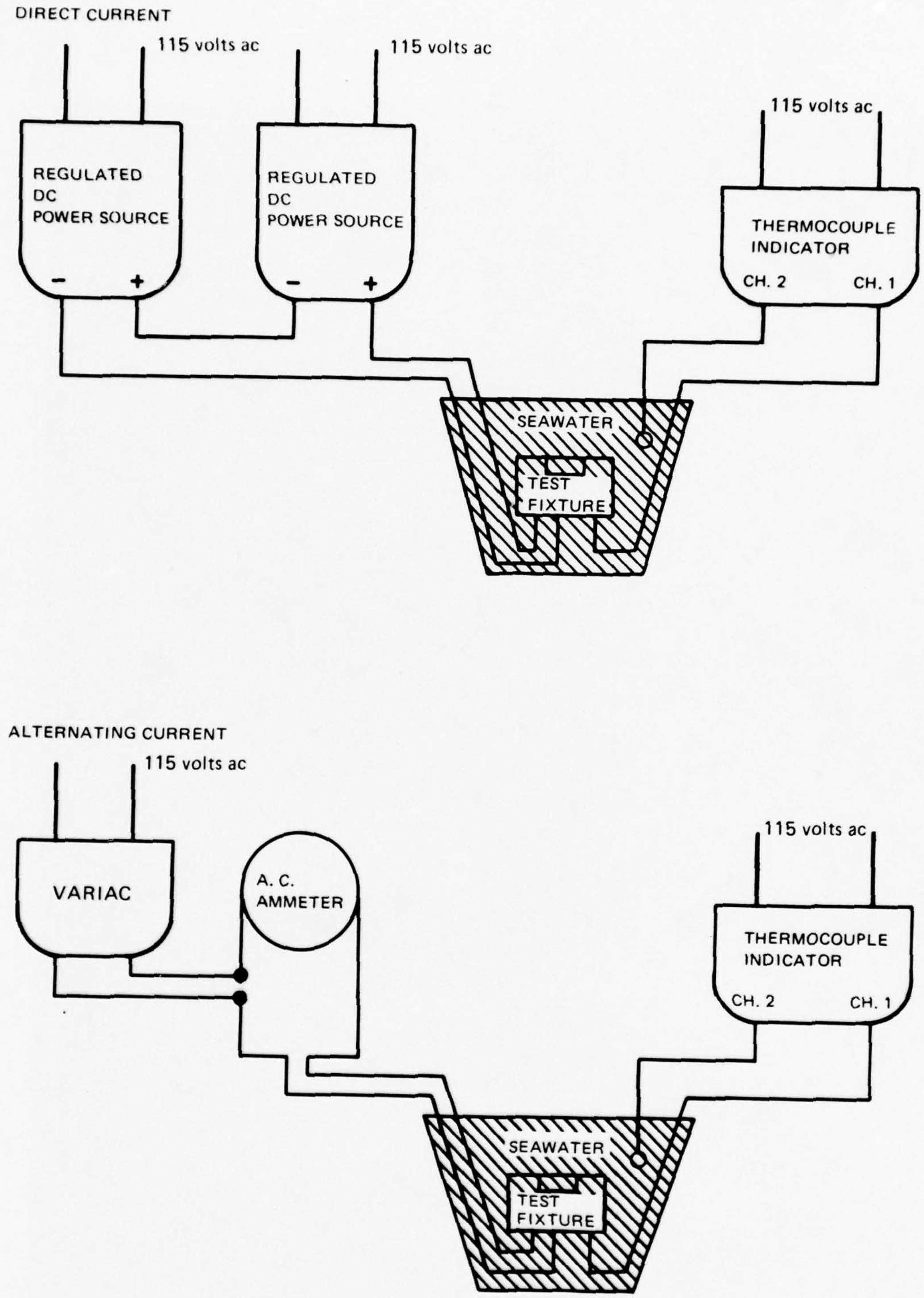


Figure 15. Indoor current tests: test set-up.

Figure 16. Text fixture being lowered into the bay on the marine railway.

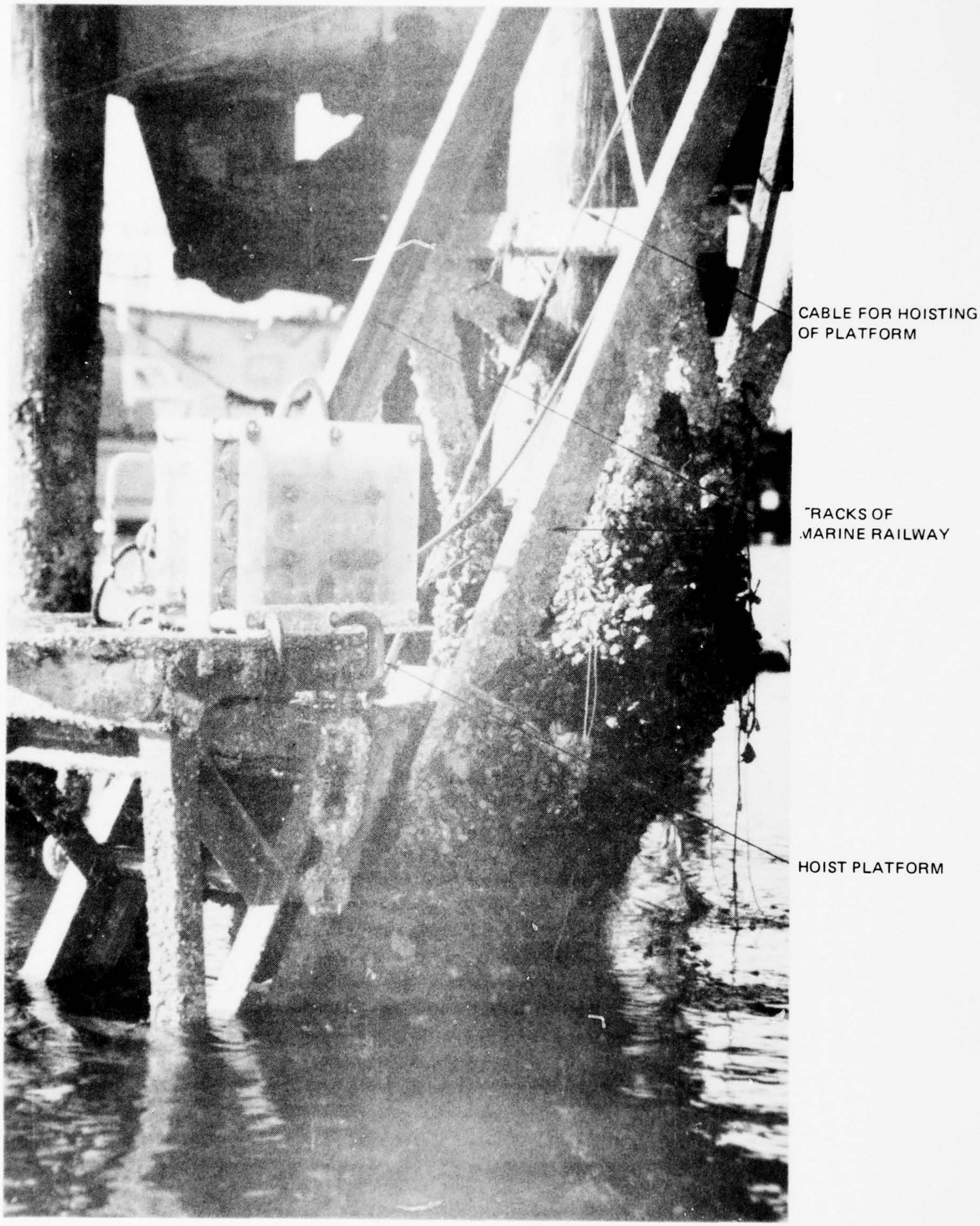


Figure 17. Test fixture B on the hoist platform.

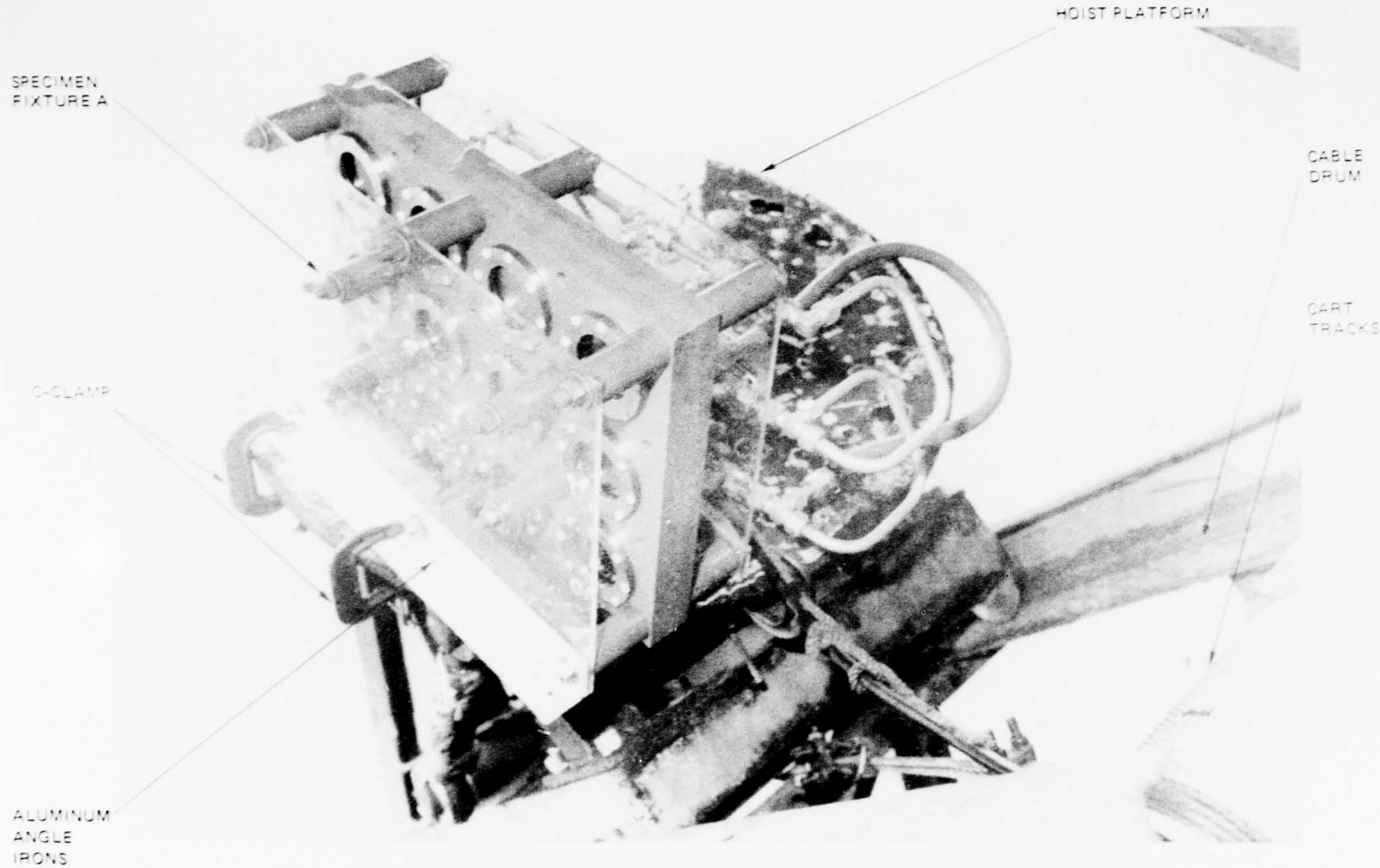


Figure 18. Test fixtures A and B placed back to back on the hoist platform.

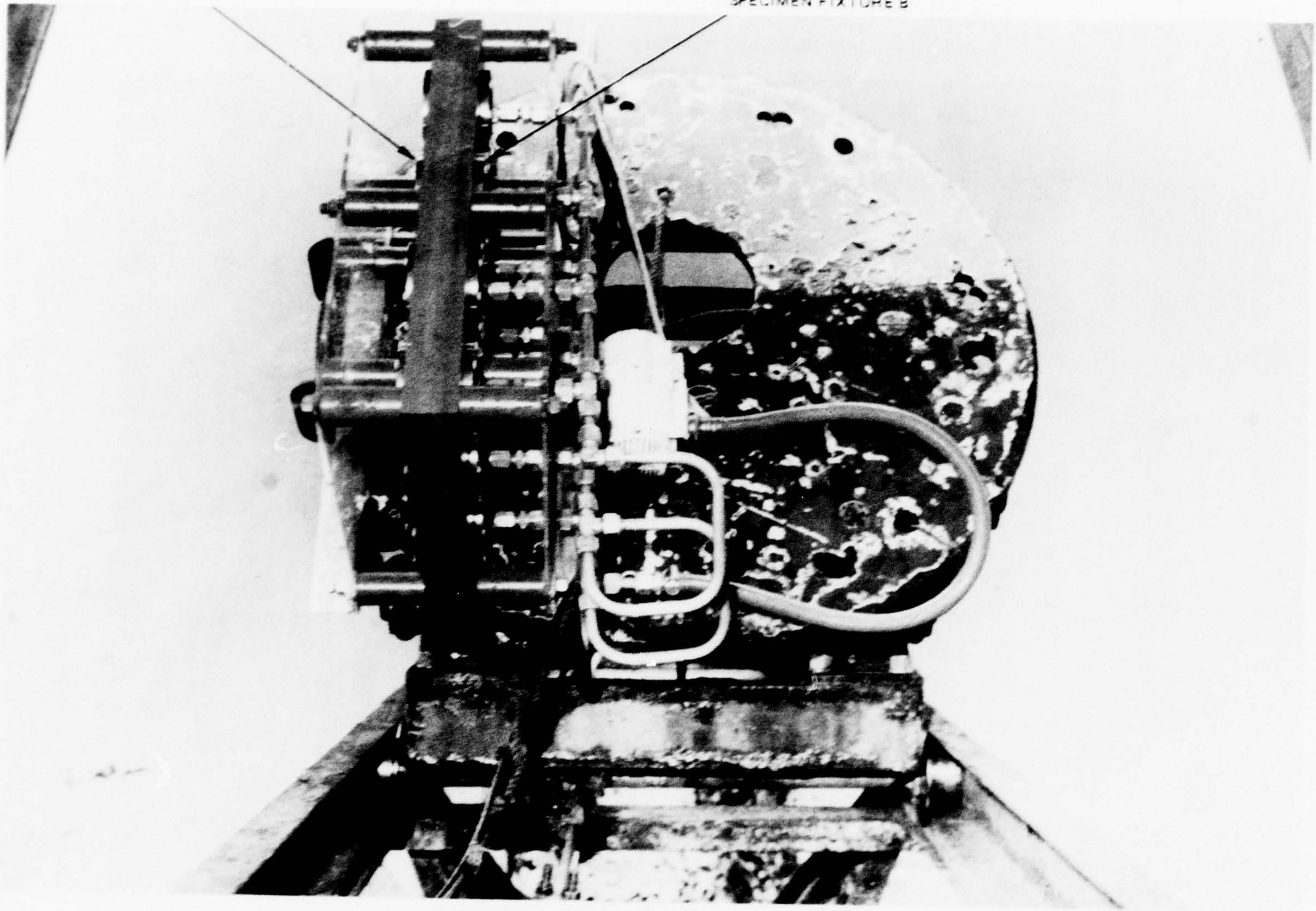


Figure 19. Test fixture A/B on the hoist.

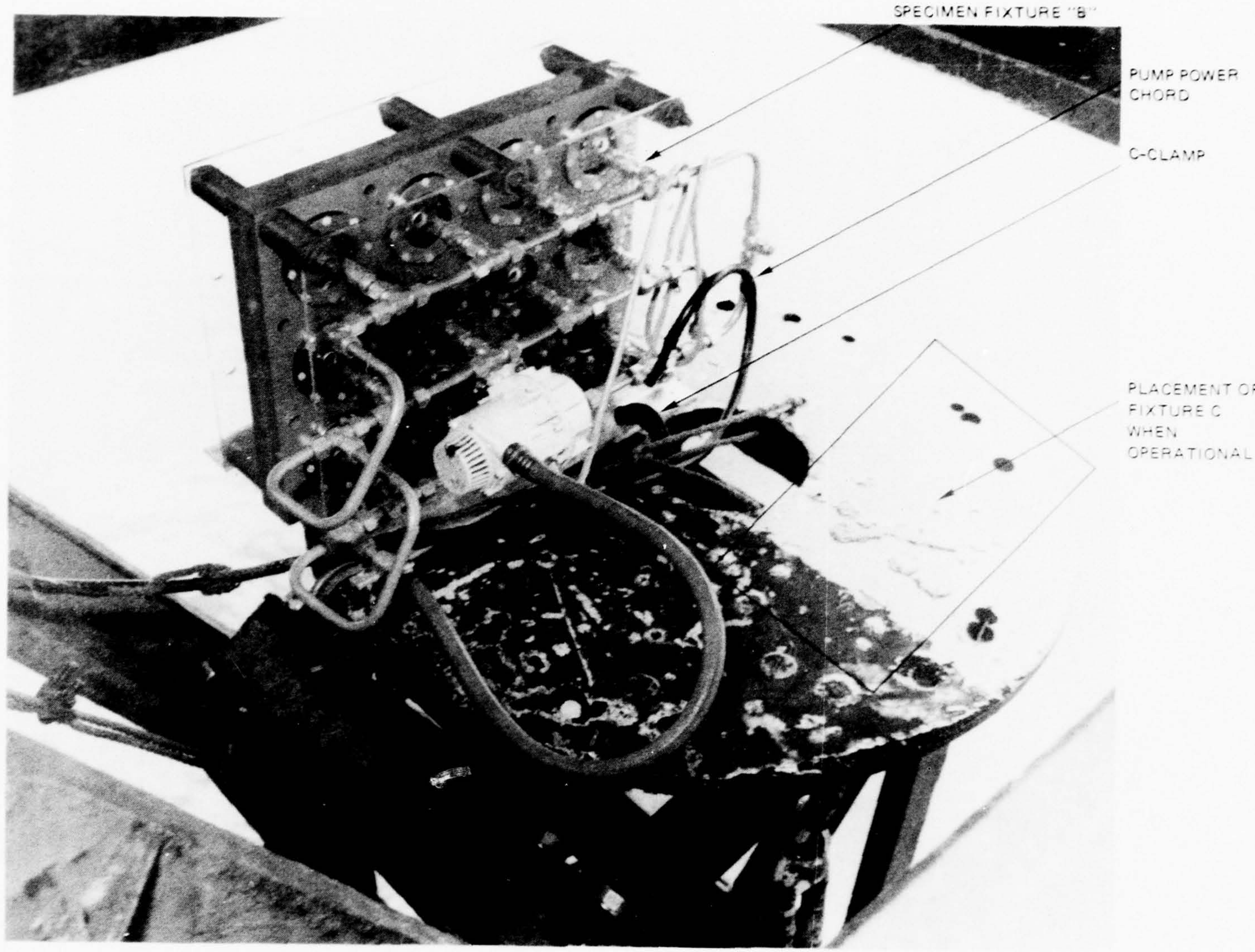


Figure 20. Test fixtures A and B on the hoist showing placement of fixture C.

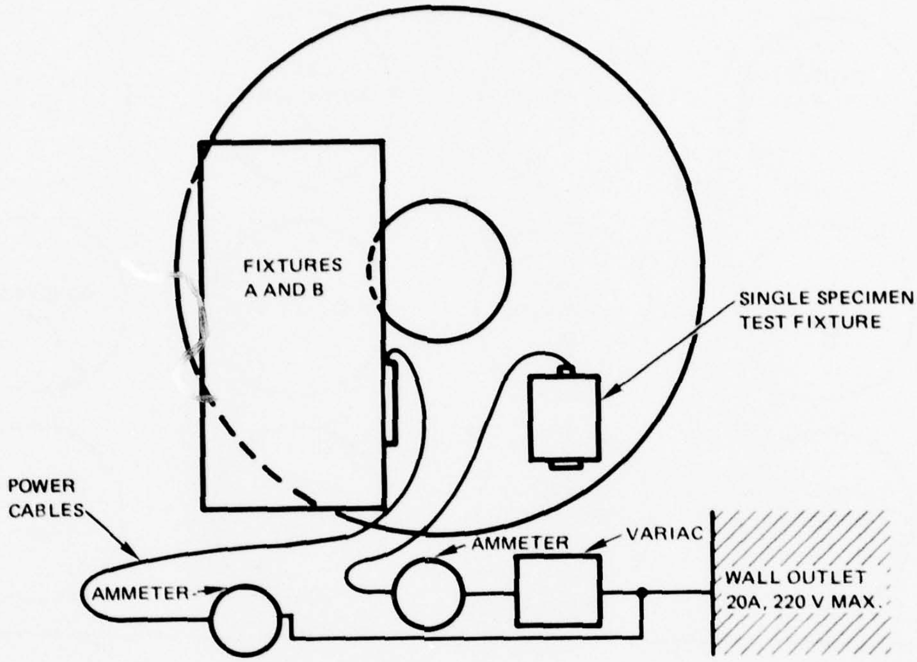


Figure 21. Location of simple specimen test fixture on hoist platform; plan view.

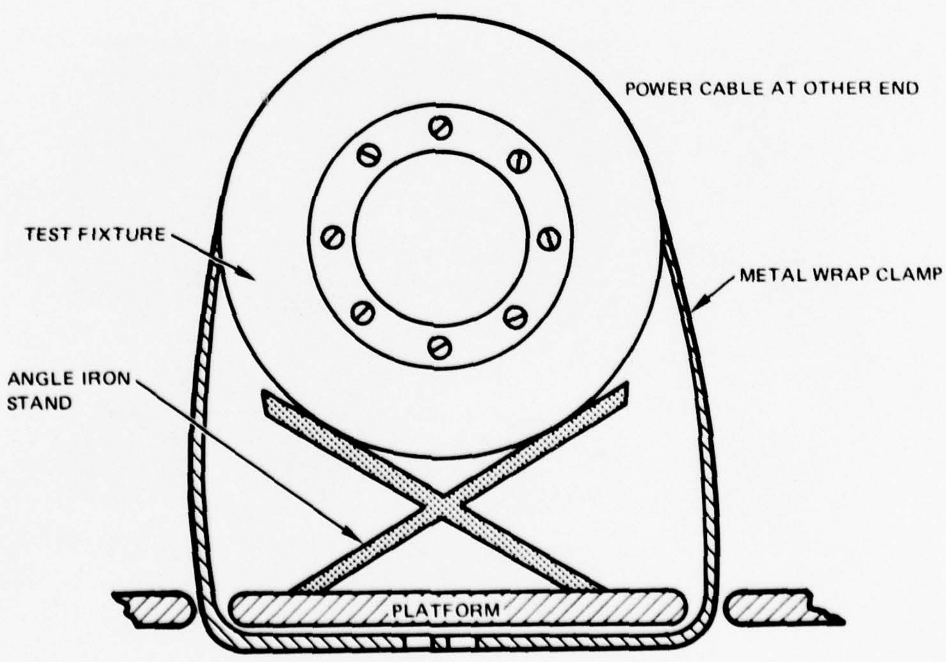


Figure 22. Attachment of single specimen test fixture to the hoist platform; elevation view.

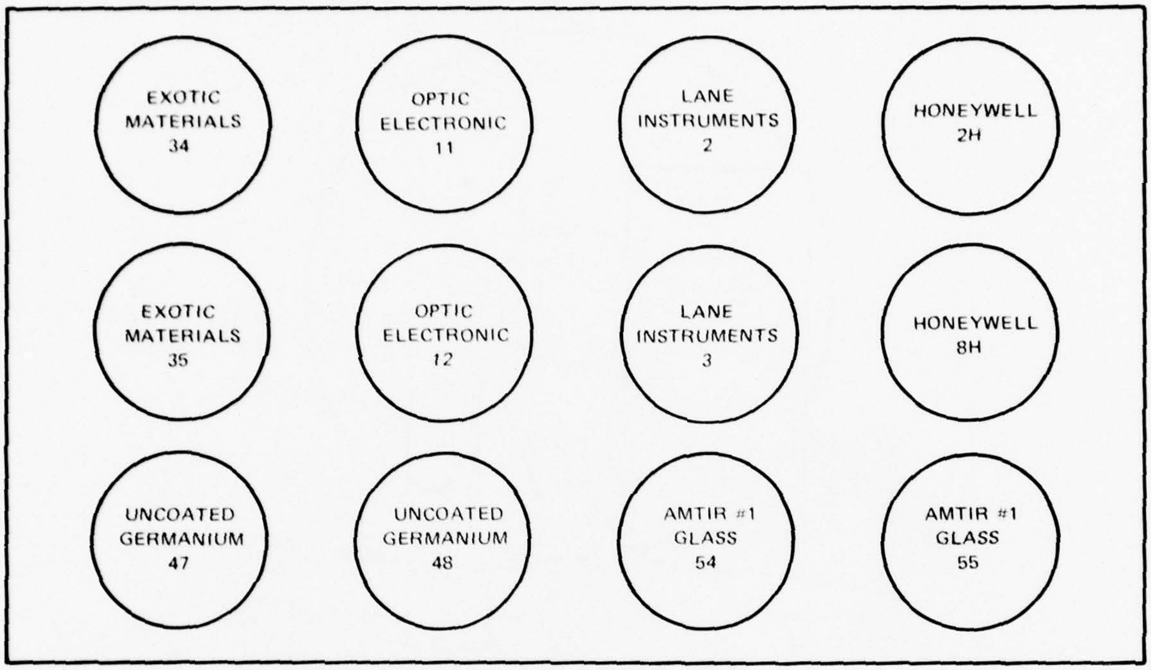


Figure 23a. Location of test specimens on test fixture A.

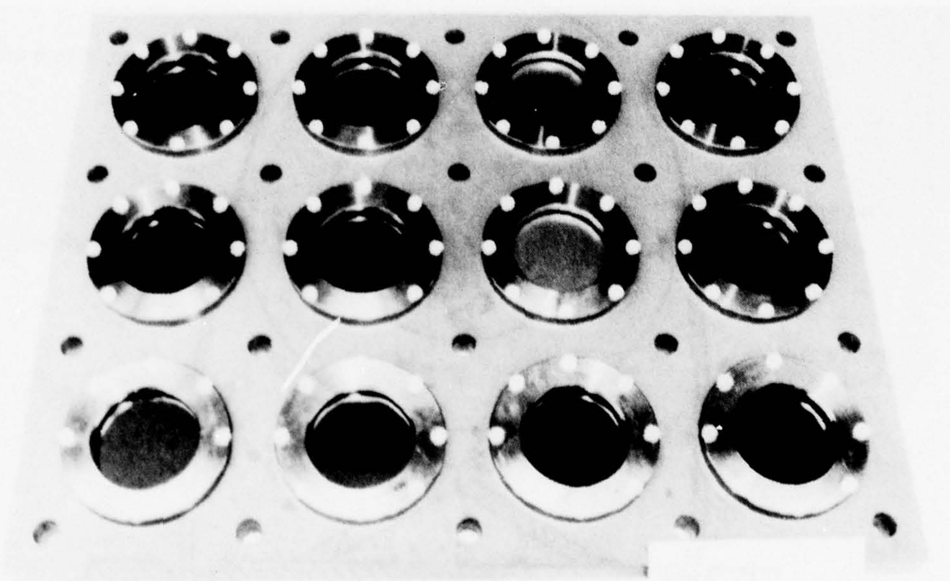


Figure 23b. Test fixture A with all test specimens in place.

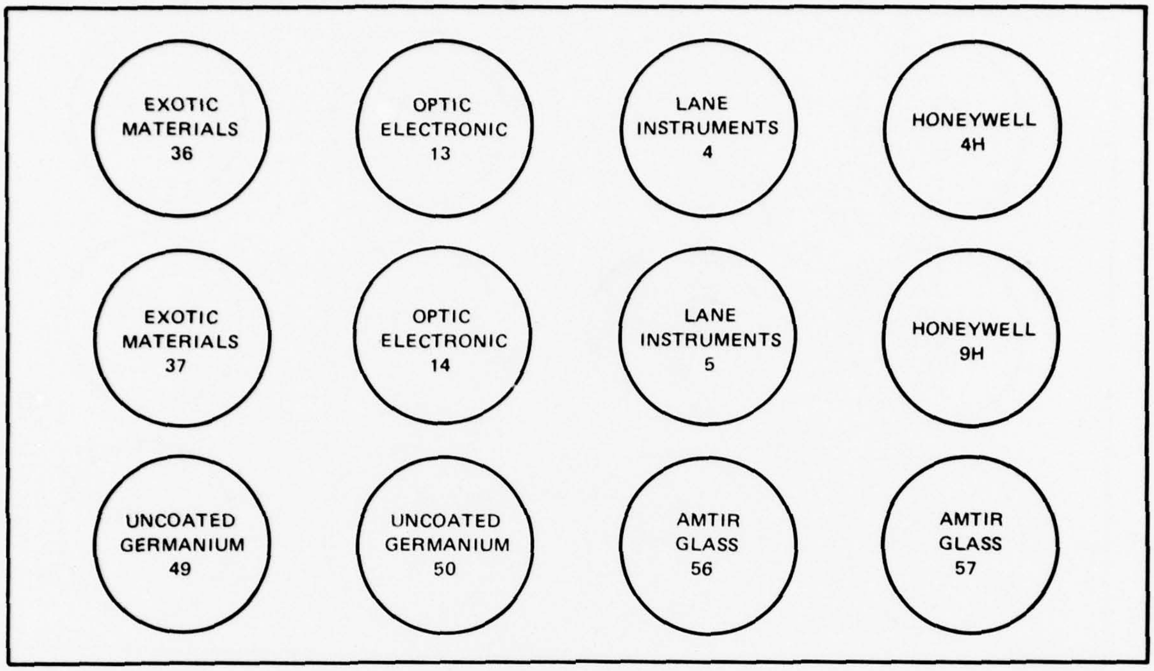


Figure 24a. Location of test specimens on test fixture B.

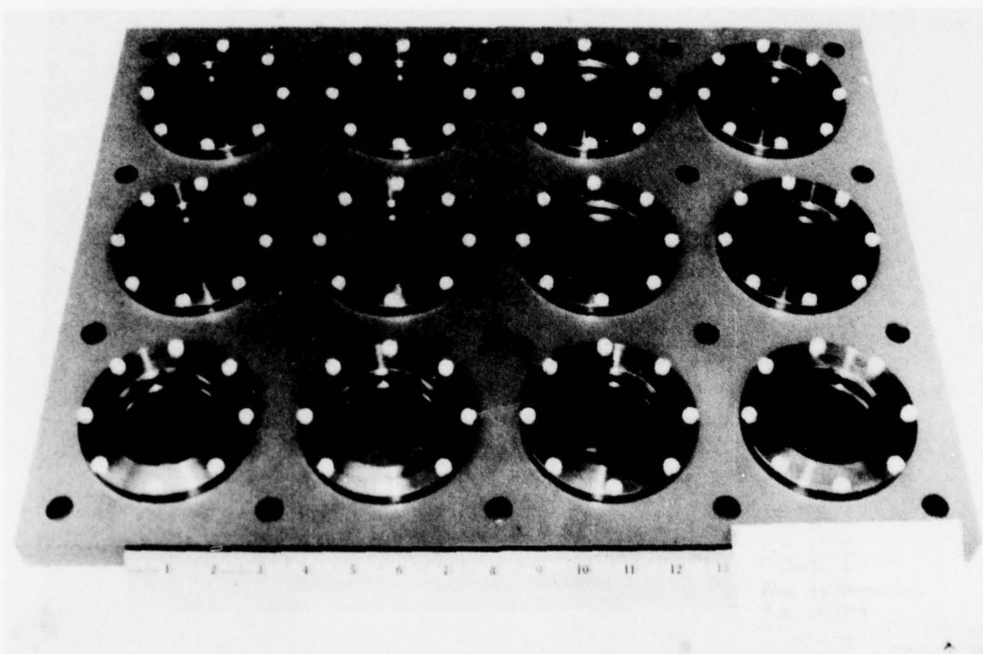


Figure 24b. Test fixture B with all test specimens in place.

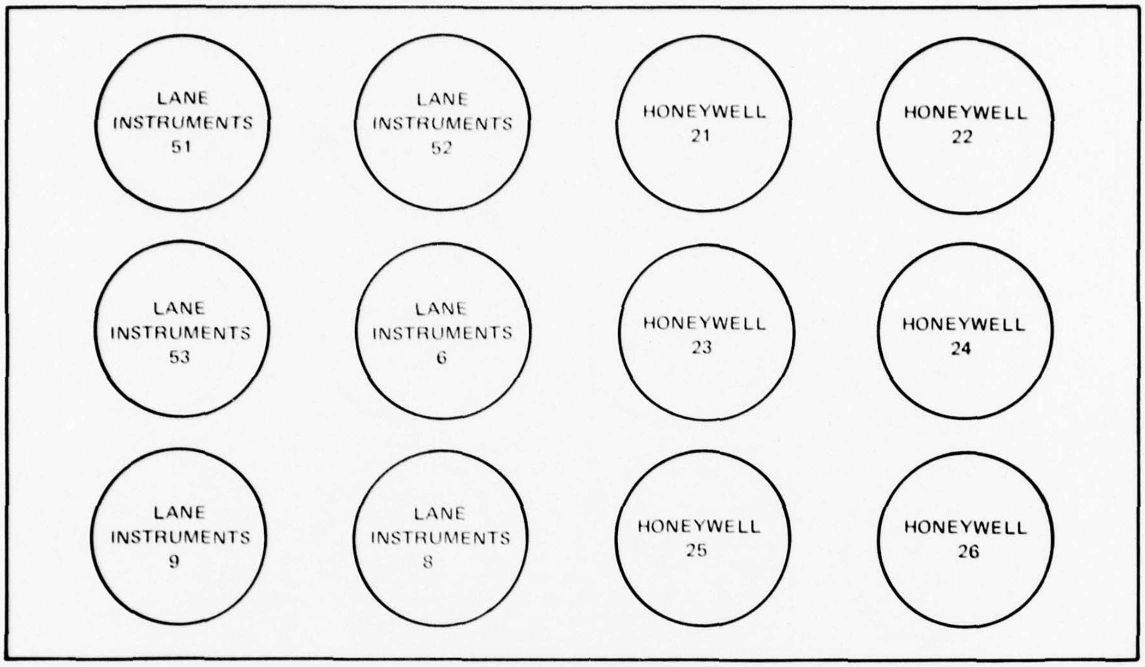


Figure 25a. Location of test specimens on test fixture C.

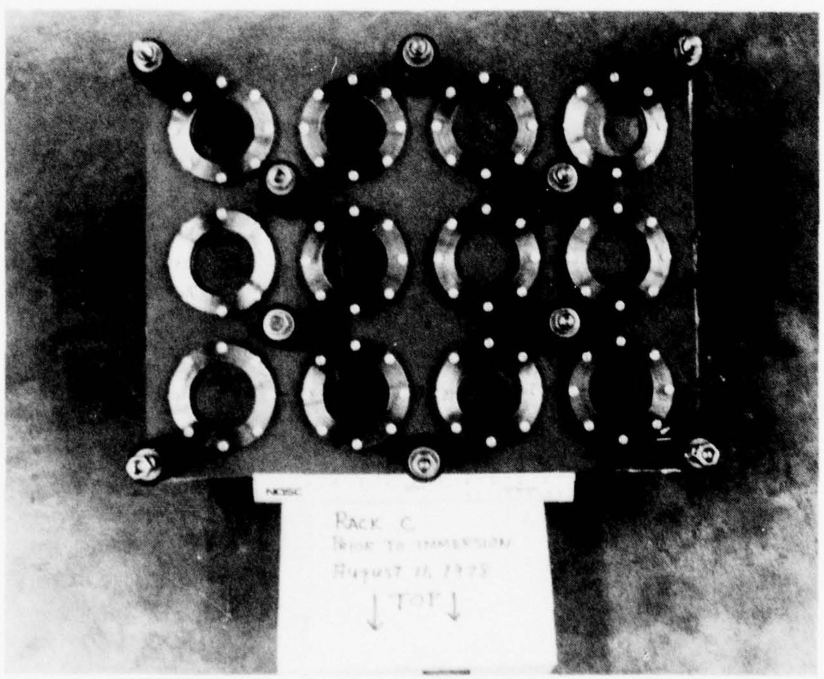


Figure 25b. Test fixture C with all test specimens in place.

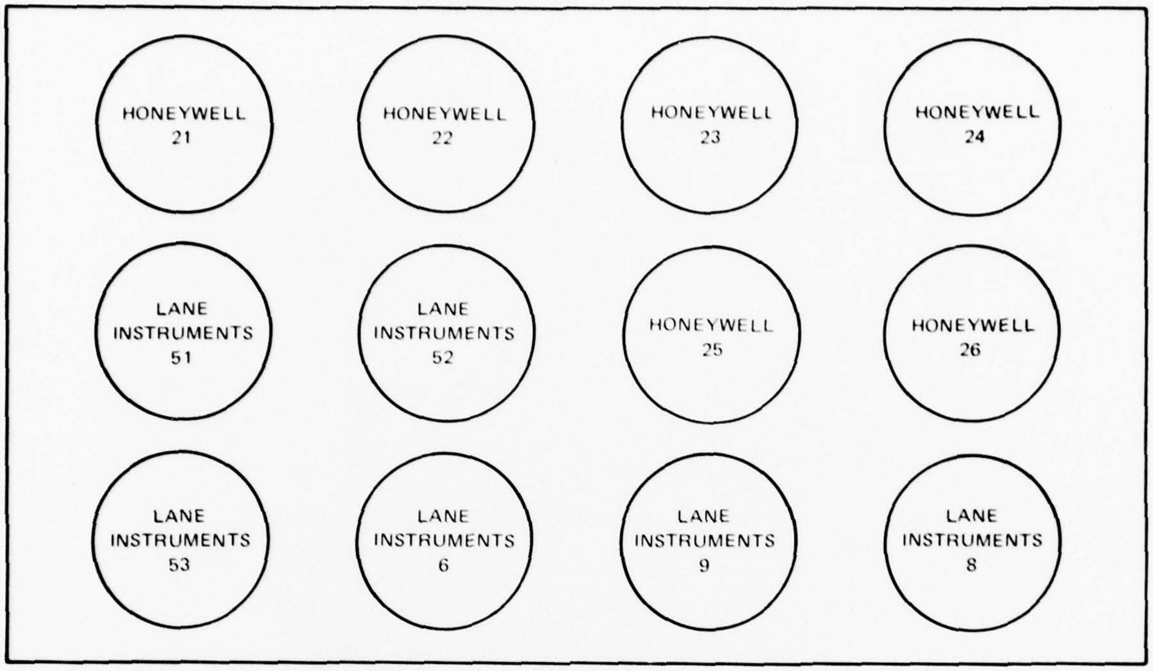


Figure 26. Text fixture C: rearranged for ease of reading remaining connected specimens.

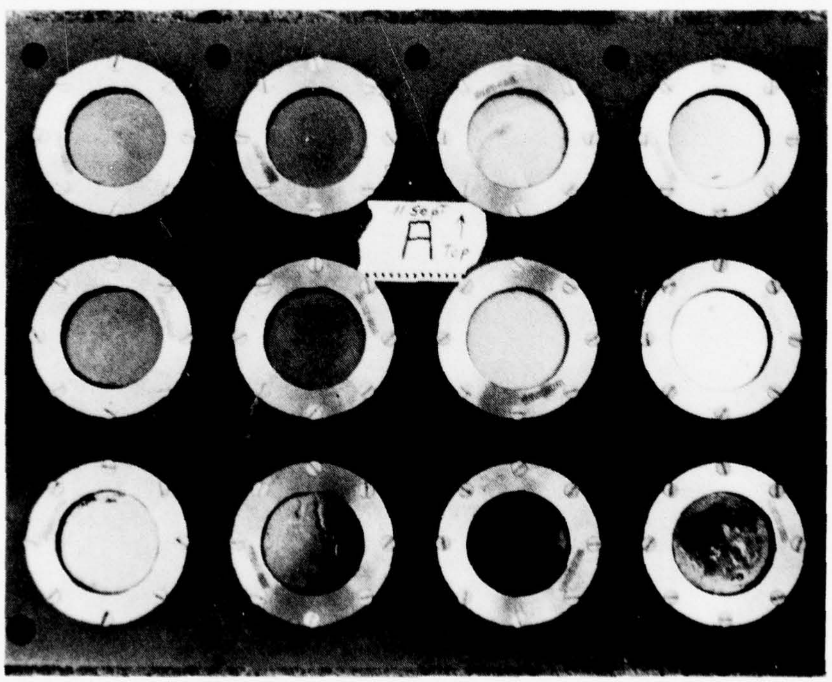


Figure 27. Test fixture A, subjected to natural circulation after one month submersion in the San Diego Bay at 35-foot depth.

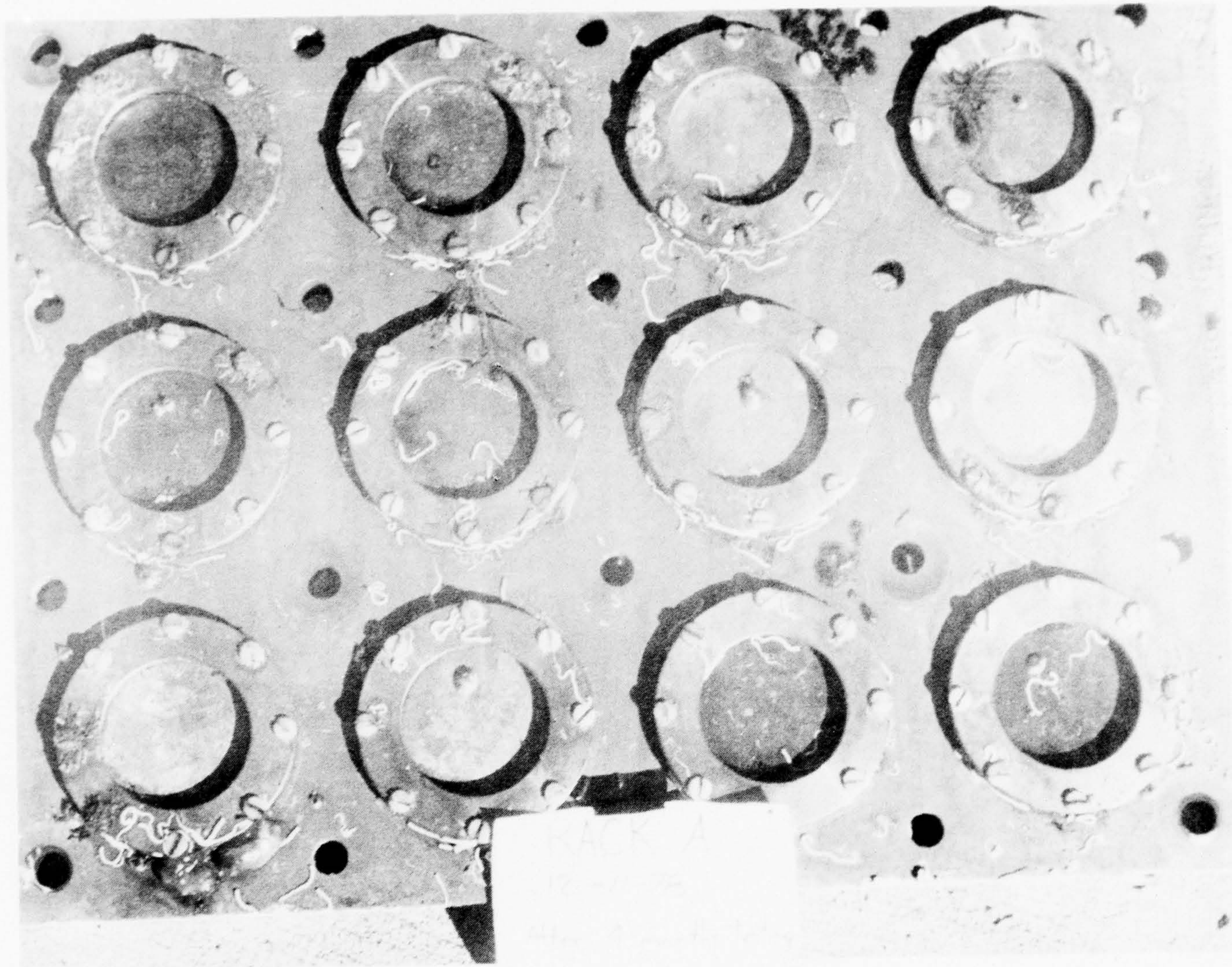


Figure 28. Test fixture A, subjected to natural circulation, after four months submersion in San Diego Bay at 35-foot depth.

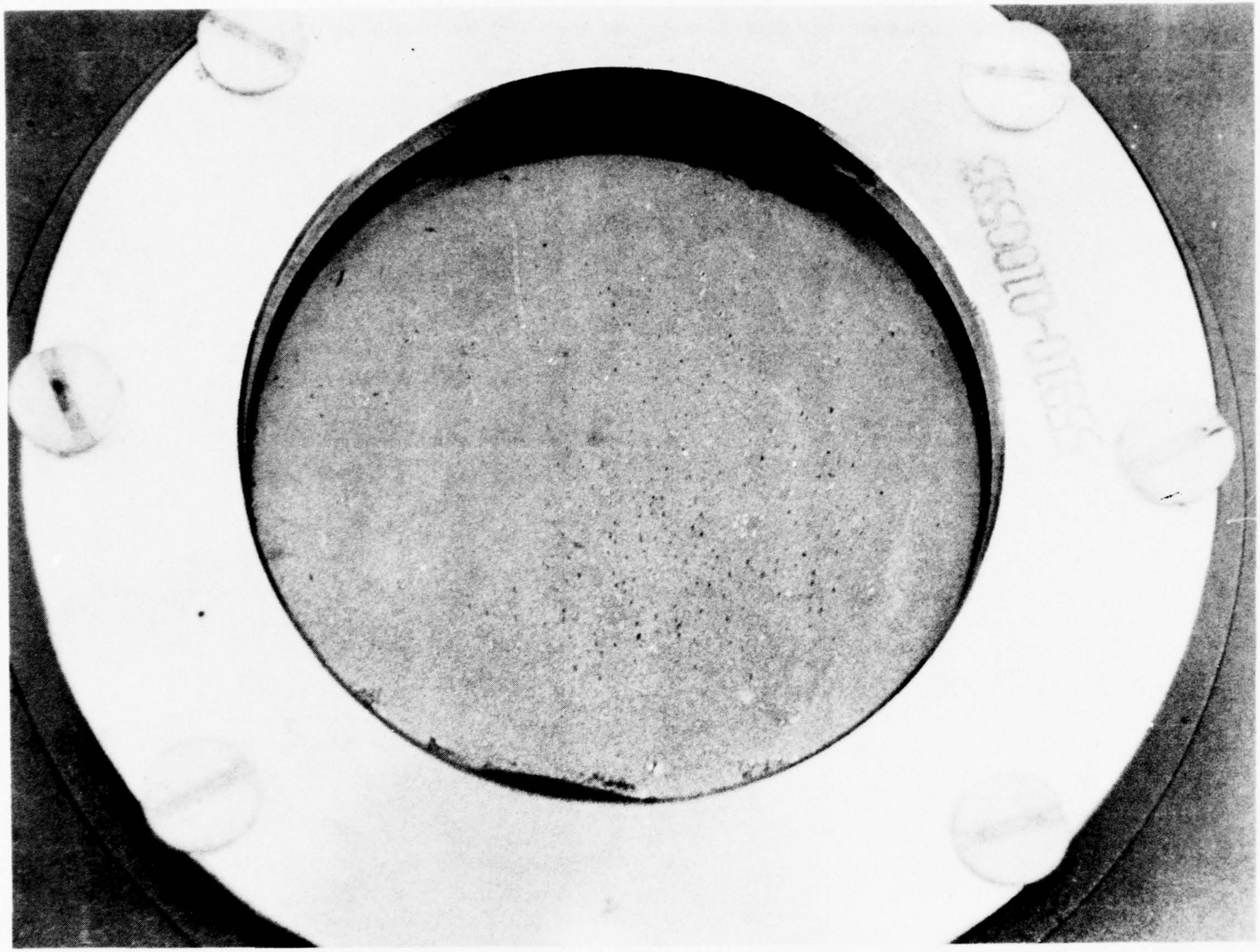


Figure 29. A specimen with Exotic Materials AR coating after one month of testing, with natural circulation, in San Diego Bay.

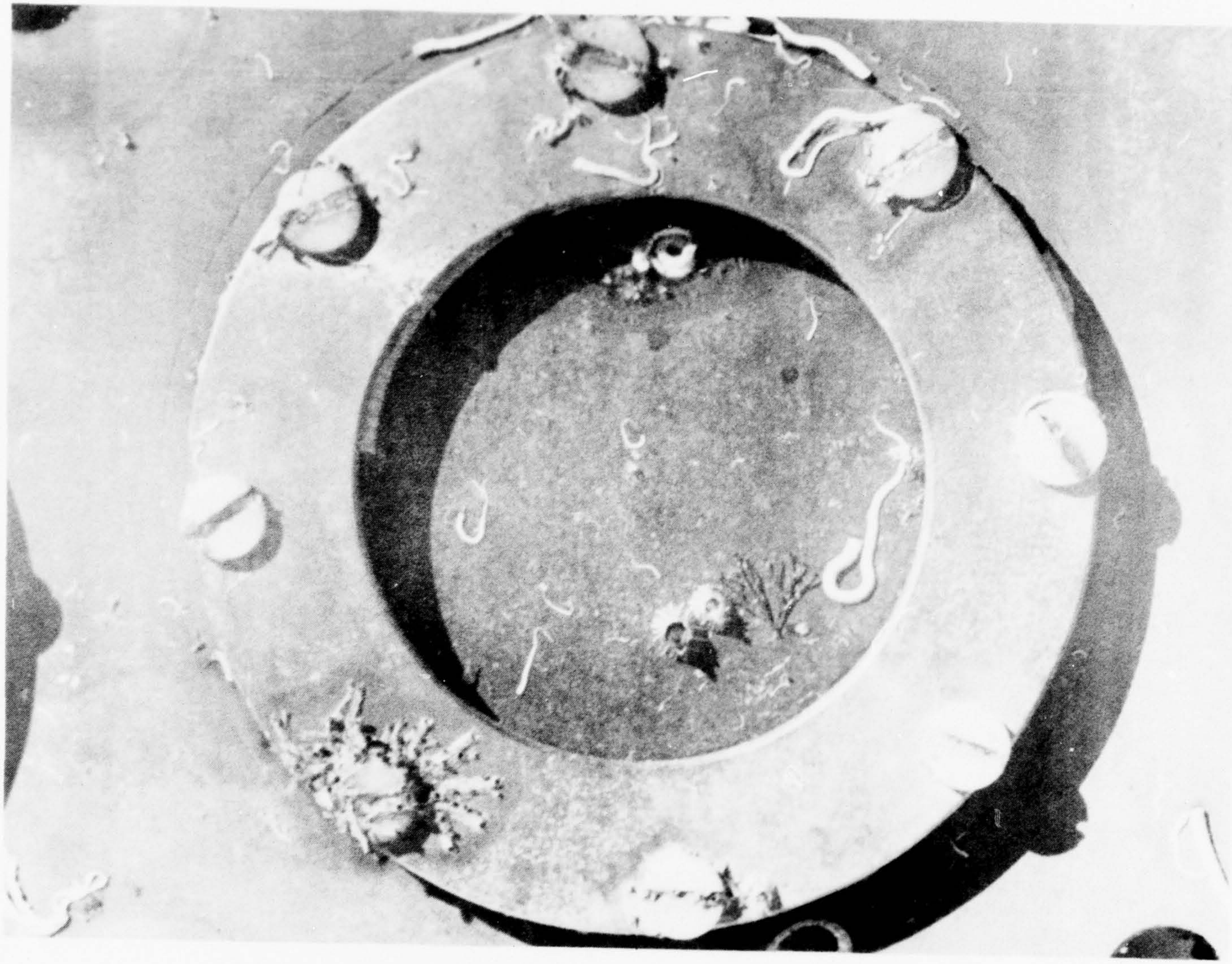


Figure 30. A specimen with Exotic Materials AR coating, after four months of testing with natural water circulation in San Diego Bay.

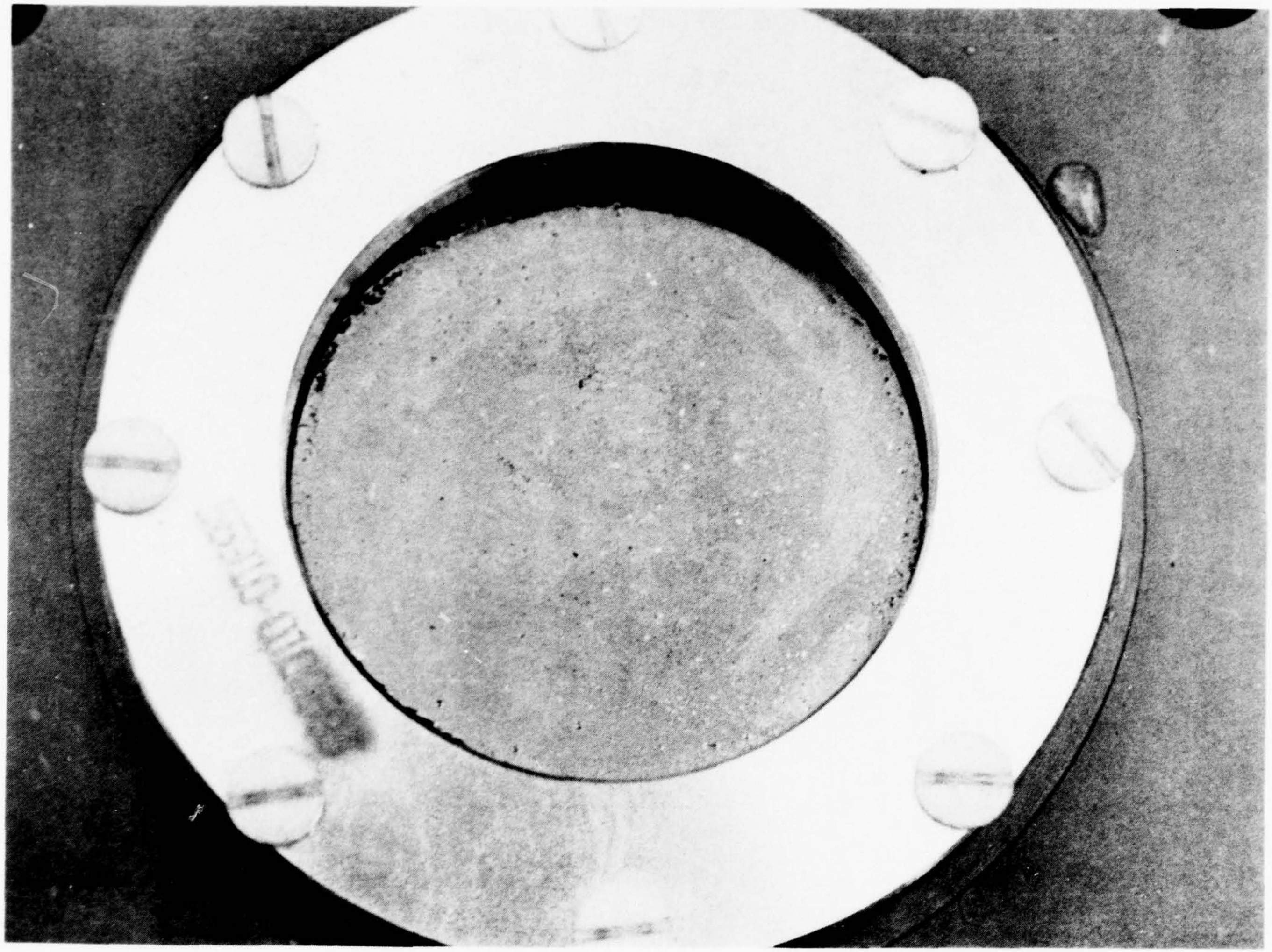


Figure 31. A specimen with the Optic Electronic AR coating after one month of testing with natural circulation in San Diego Bay.

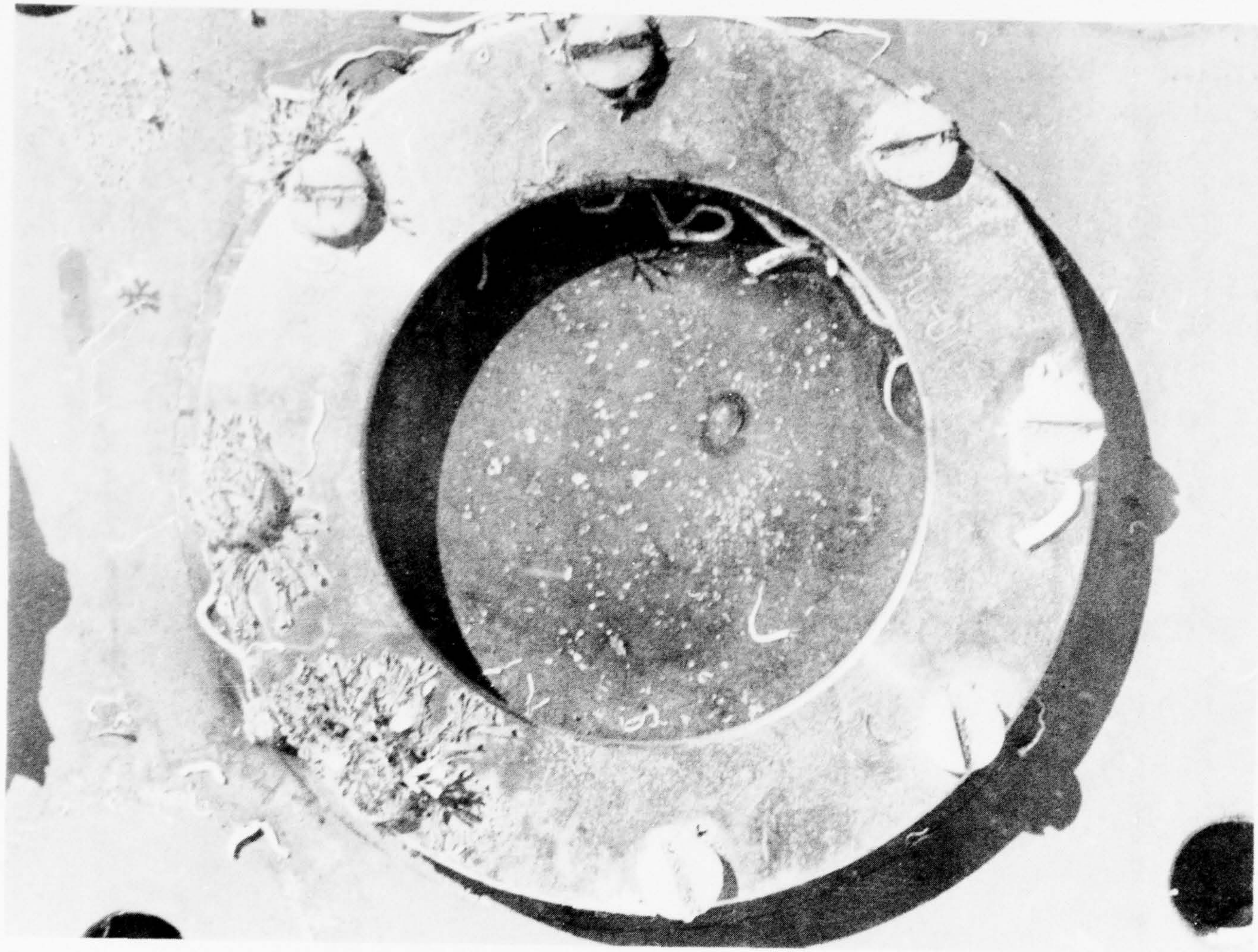


Figure 32. A specimen with the Optic Electronic AR coating after four months of testing with natural circulation in San Diego Bay.

Figure 33. A specimen with the Honeywell PE/PP/PE plastic overlay after one month of testing with natural circulation in San Diego Bay.

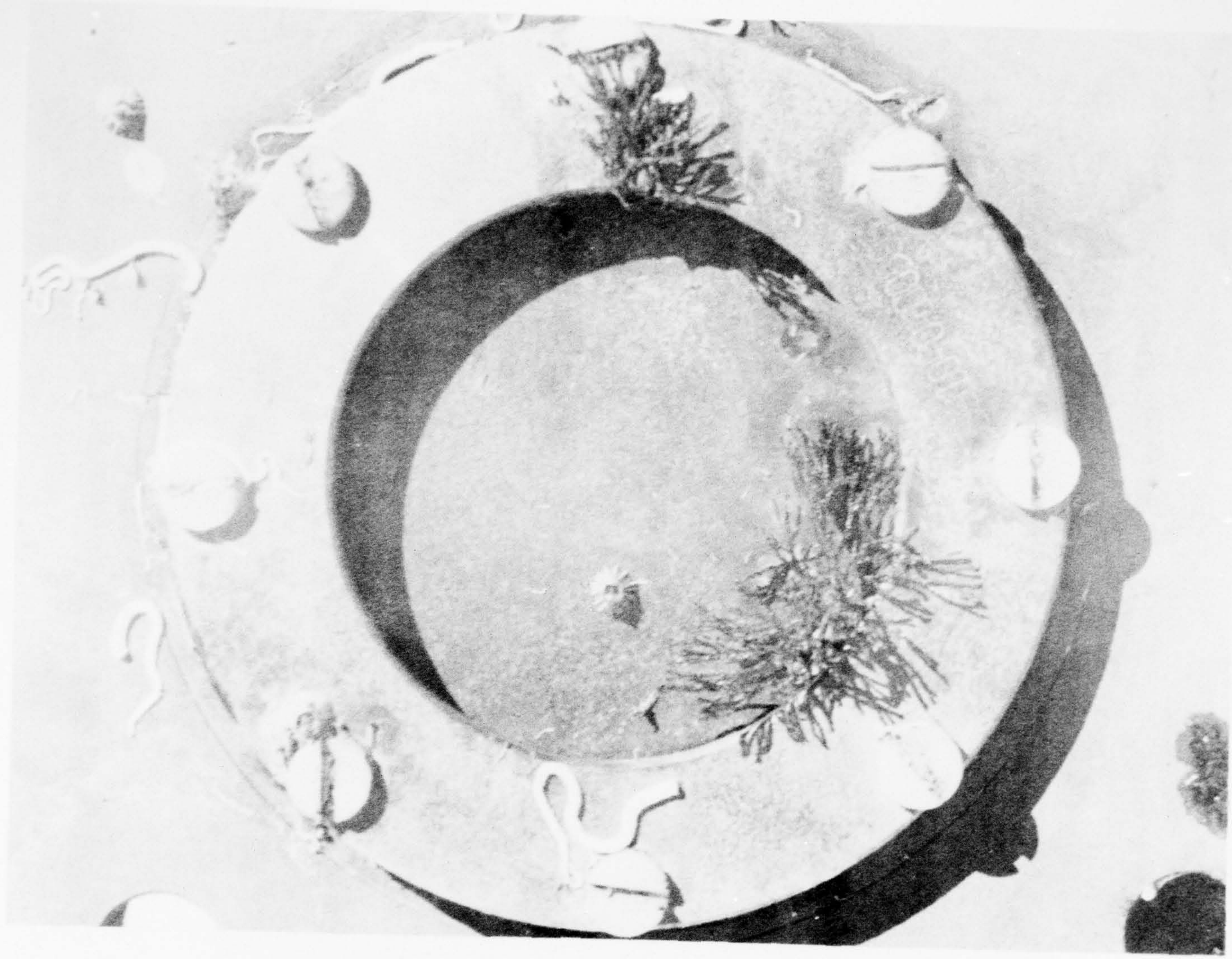


Figure 34. A specimen coated with the Honeywell PE/PP/PE plastic overlay after four months of testing with natural circulation in San Diego Bay.

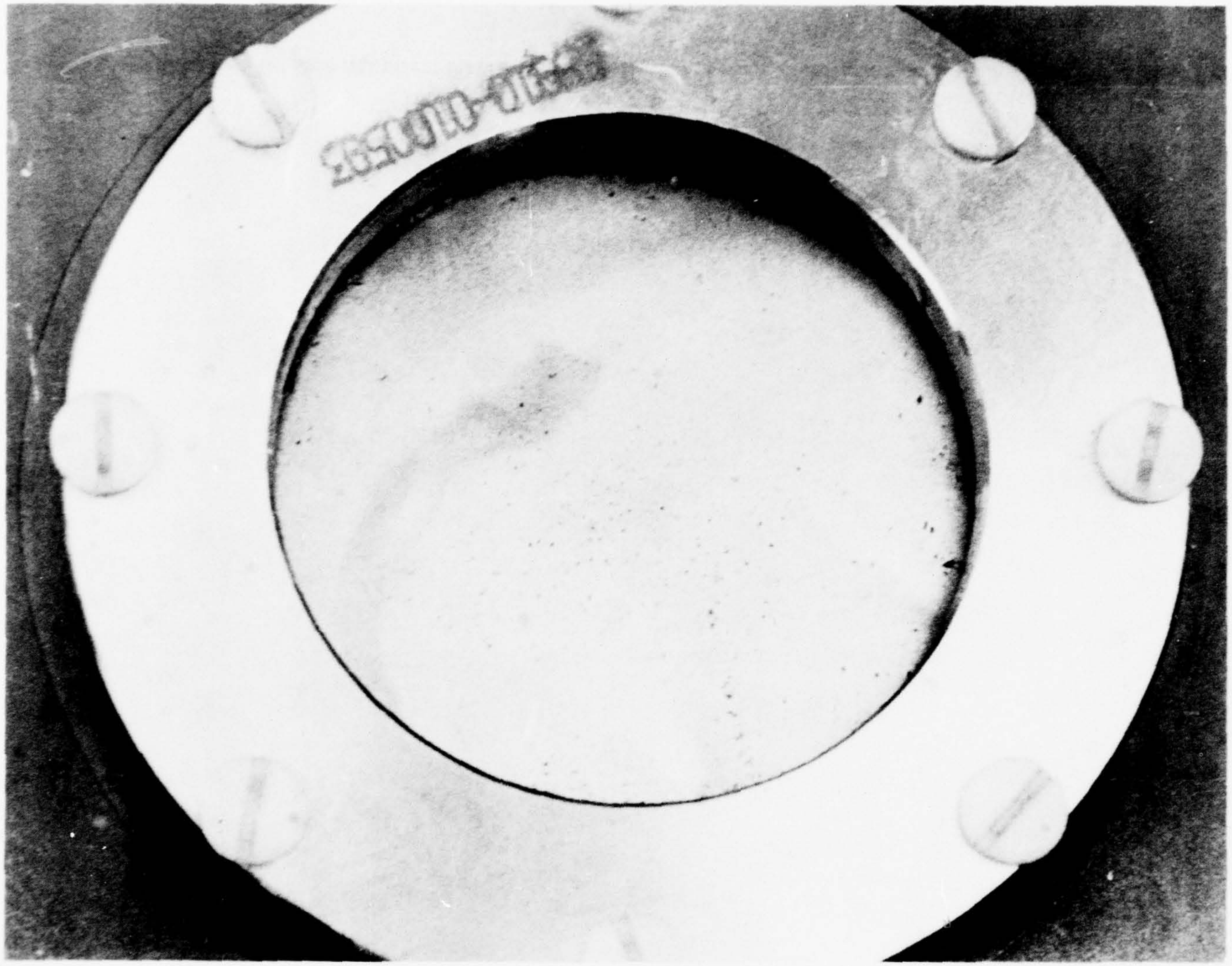


Figure 35. A specimen with the Lane Instrument PO plastic overlay after one month of testing with natural circulation in San Diego Bay.

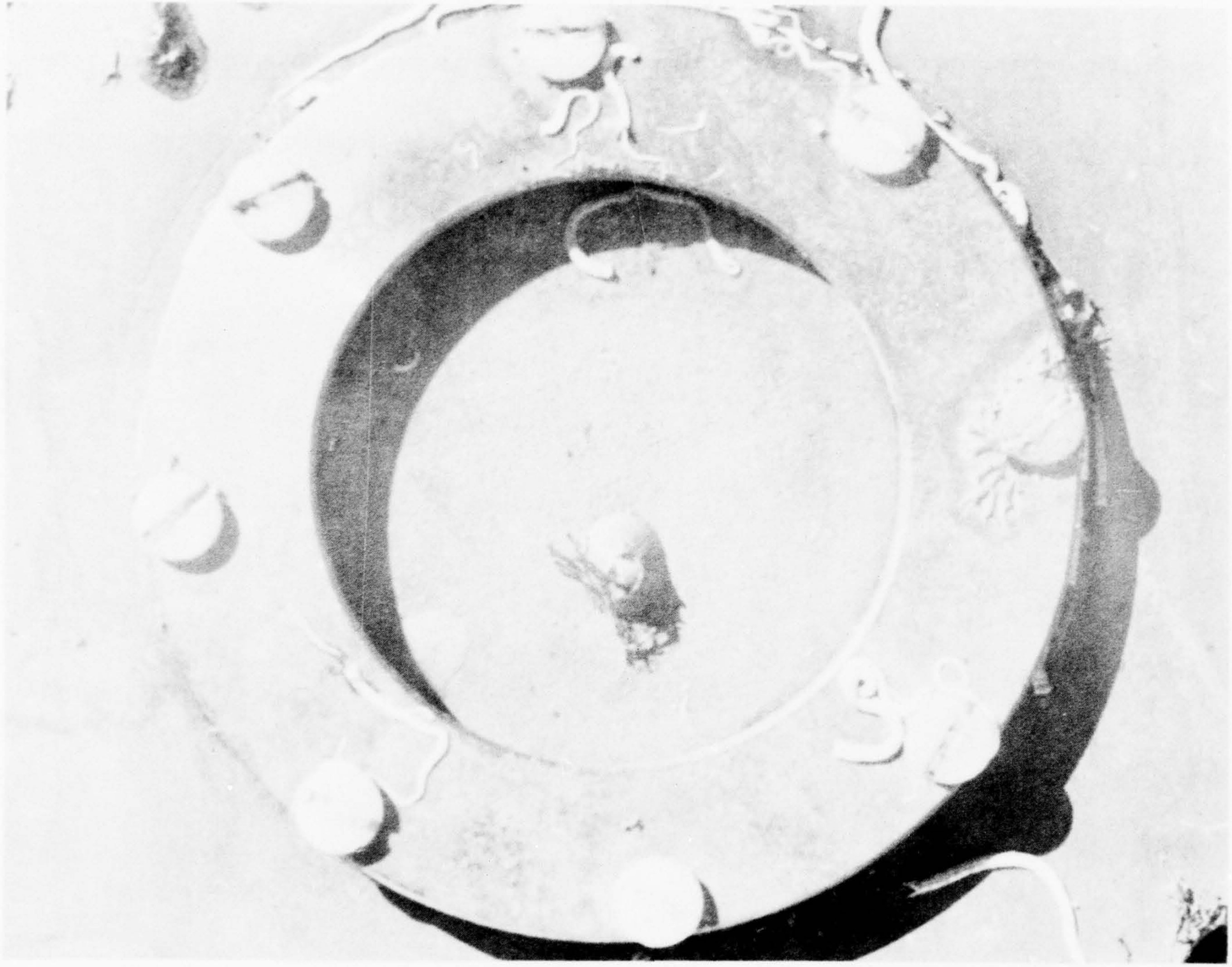


Figure 36. A specimen with the Lane Instrument PO plastic overlay after four months of testing with natural circulation in San Diego Bay.

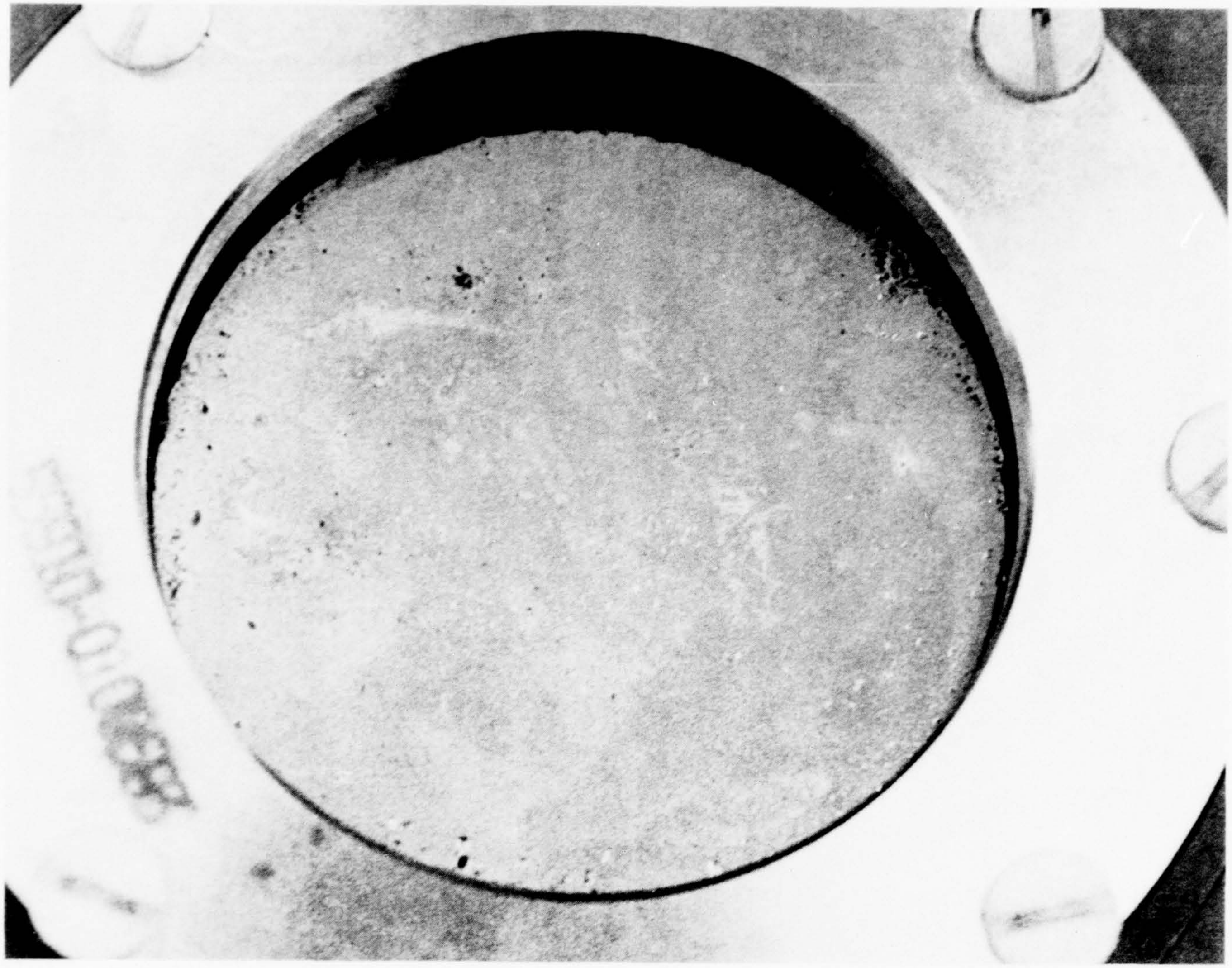


Figure 37. An uncoated germanium specimen after one month of testing in San Diego Bay, with natural circulation.

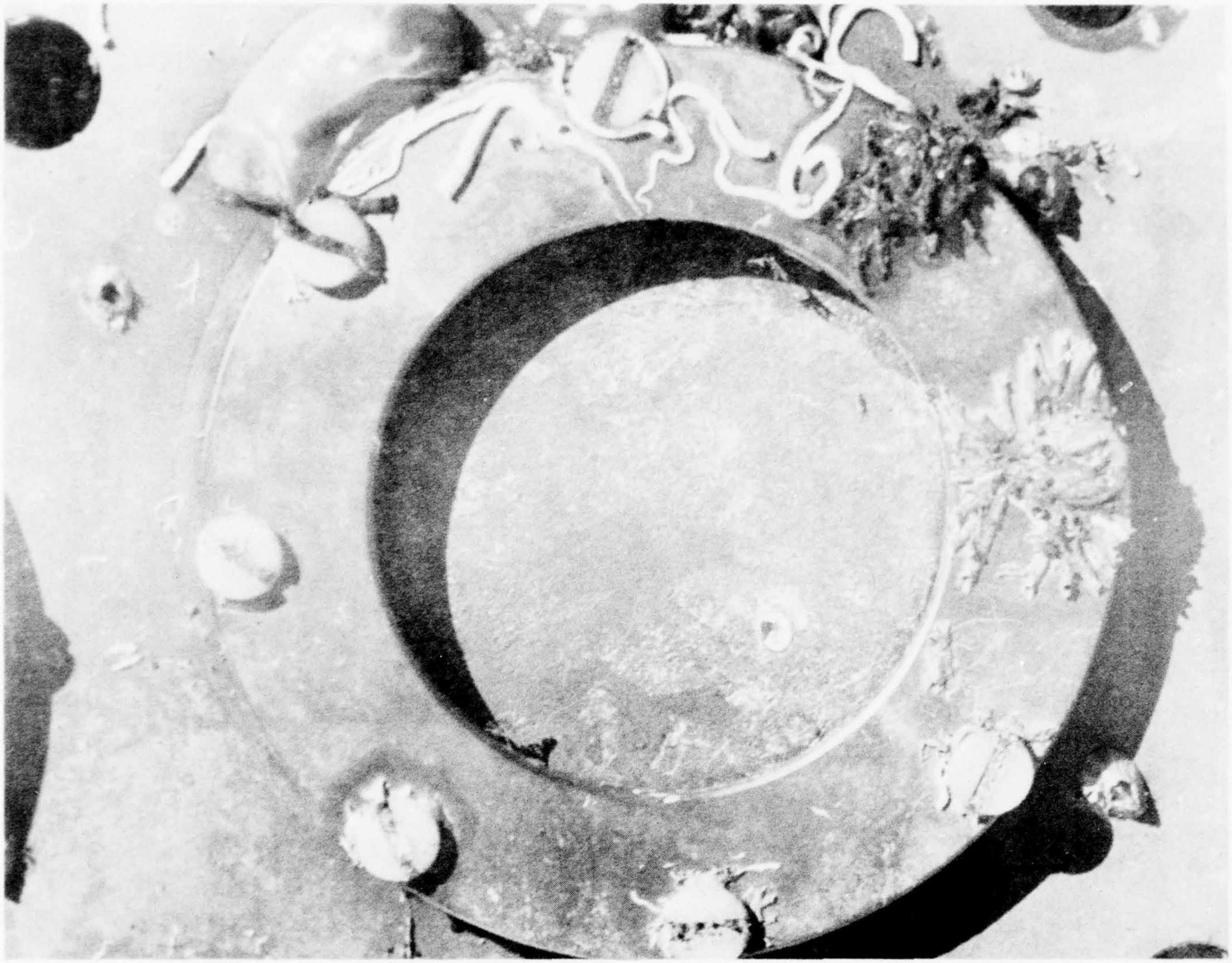


Figure 38. An uncoated germanium specimen after four months of testing in San Diego Bay, with natural circulation.

Figure 39. A specimen of AMTIR-1 glass after one month of testing with natural circulation in San Diego Bay.

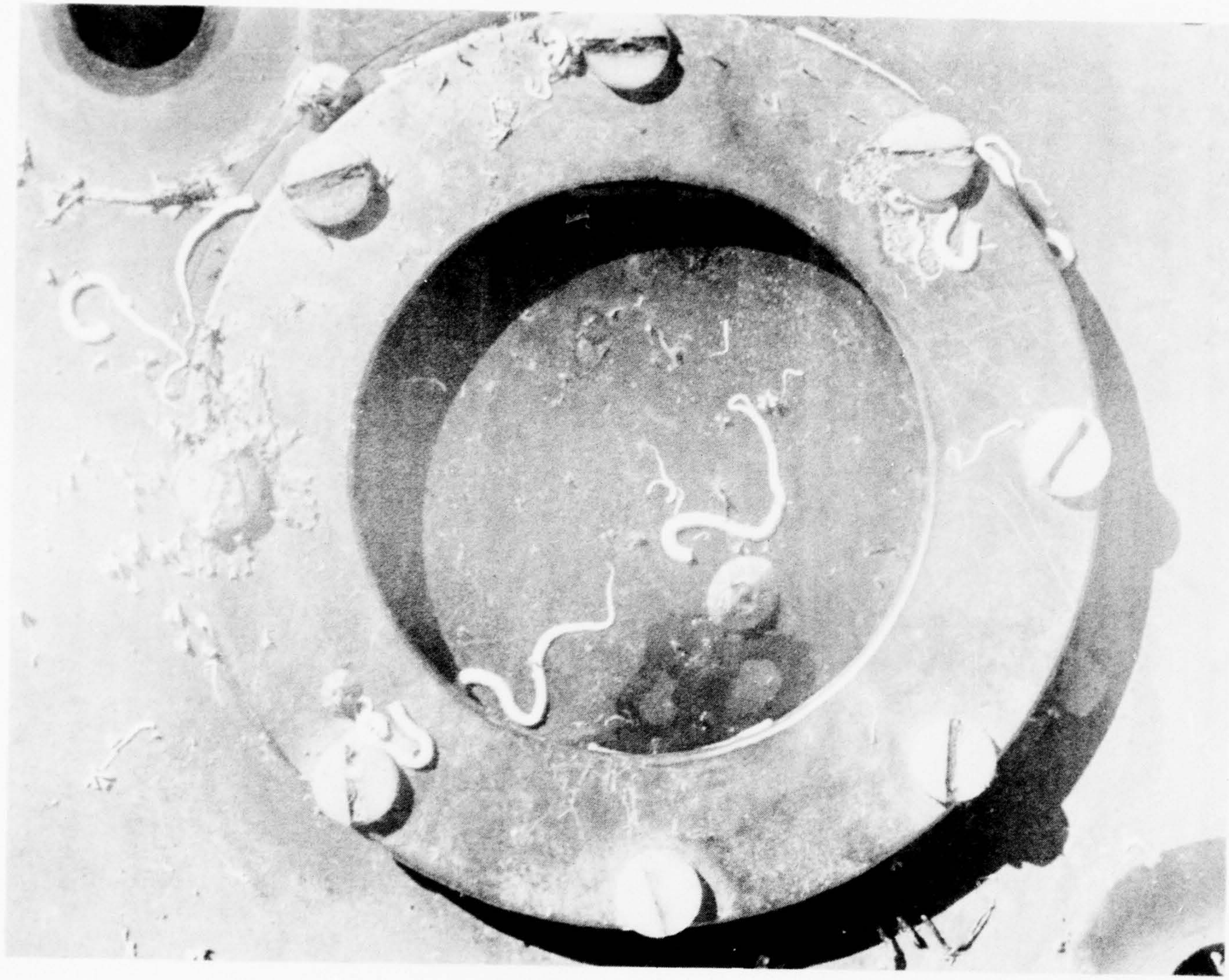


Figure 40. A specimen of AMTIR-1 glass after four months of testing with natural circulation in San Diego Bay.

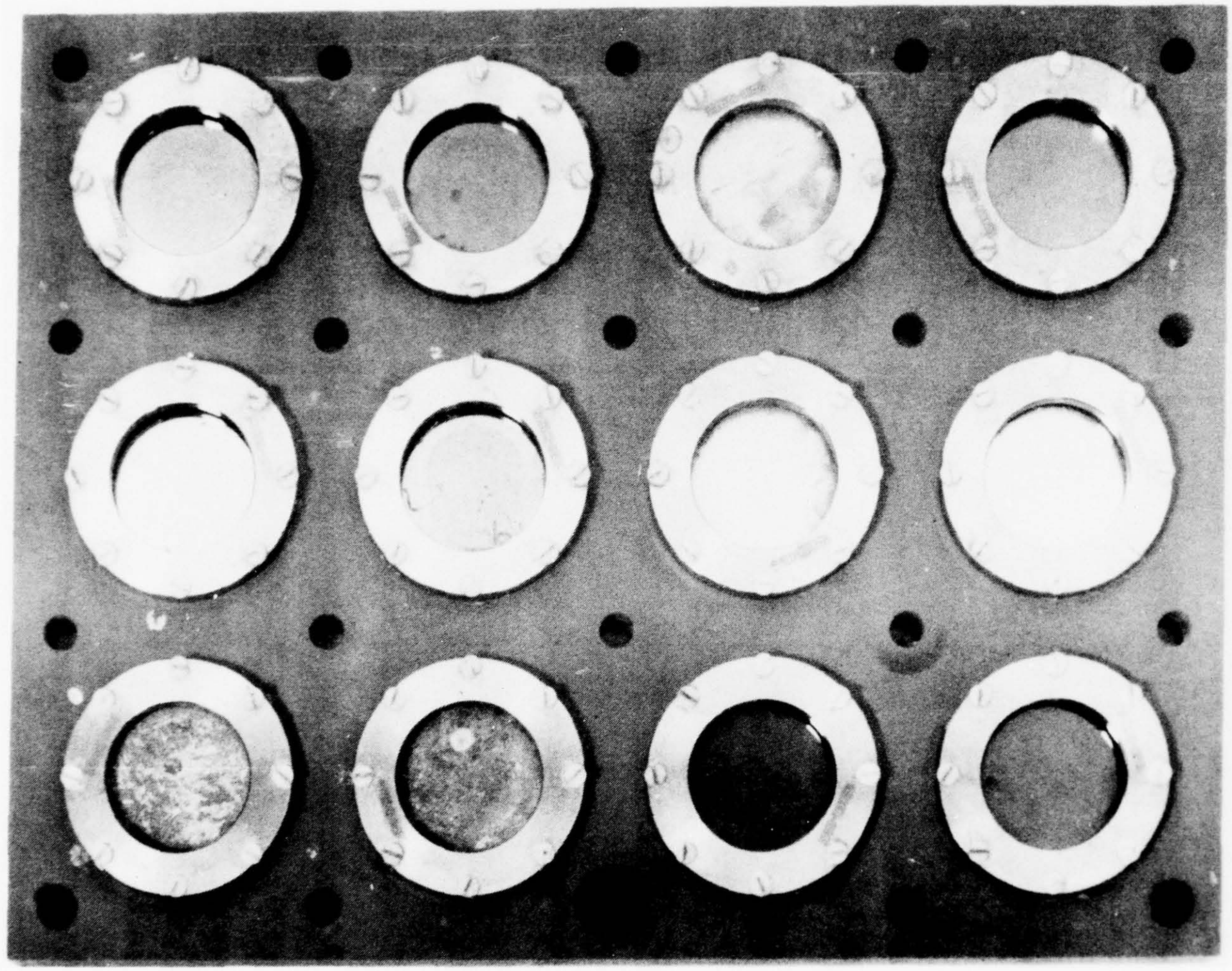


Figure 41. Test fixture A, utilizing natural circulation after four months of testing. Growth has been removed to facilitate viewing the condition of specimens.

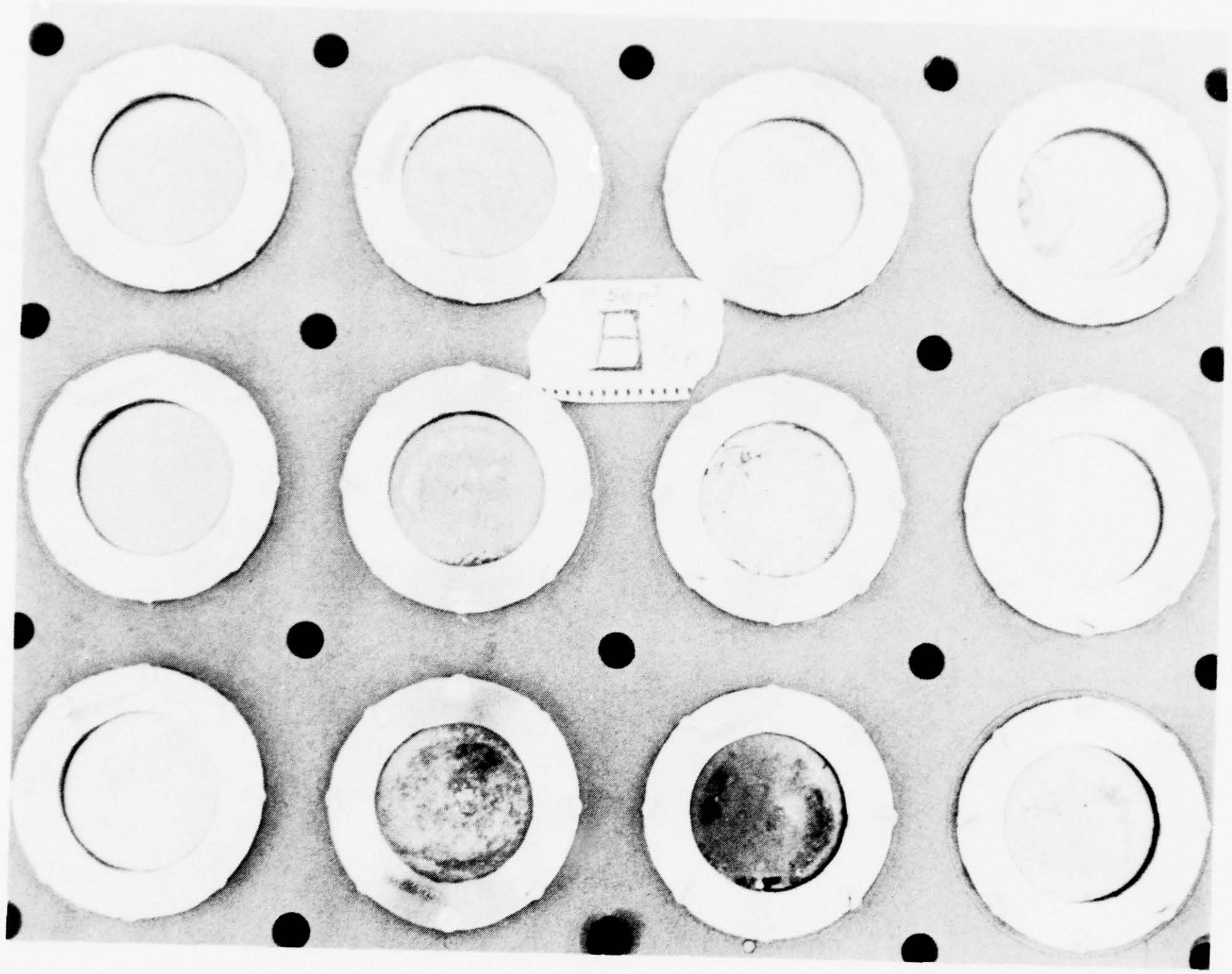


Figure 42. Test fixture B, with forced circulation after one month of testing in San Diego Bay.

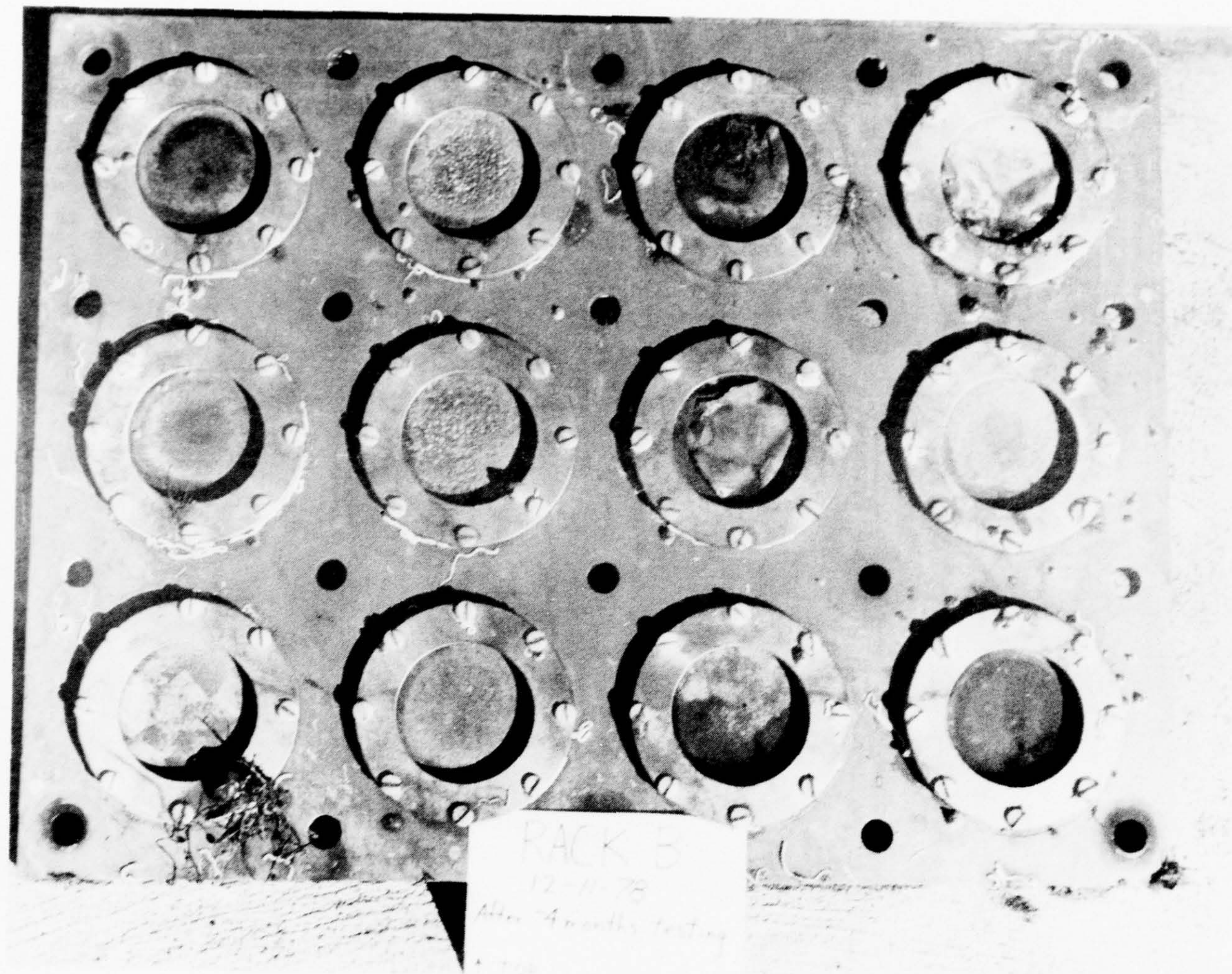


Figure 43. Test fixture B, with forced circulation, after four months of testing in San Diego Bay.

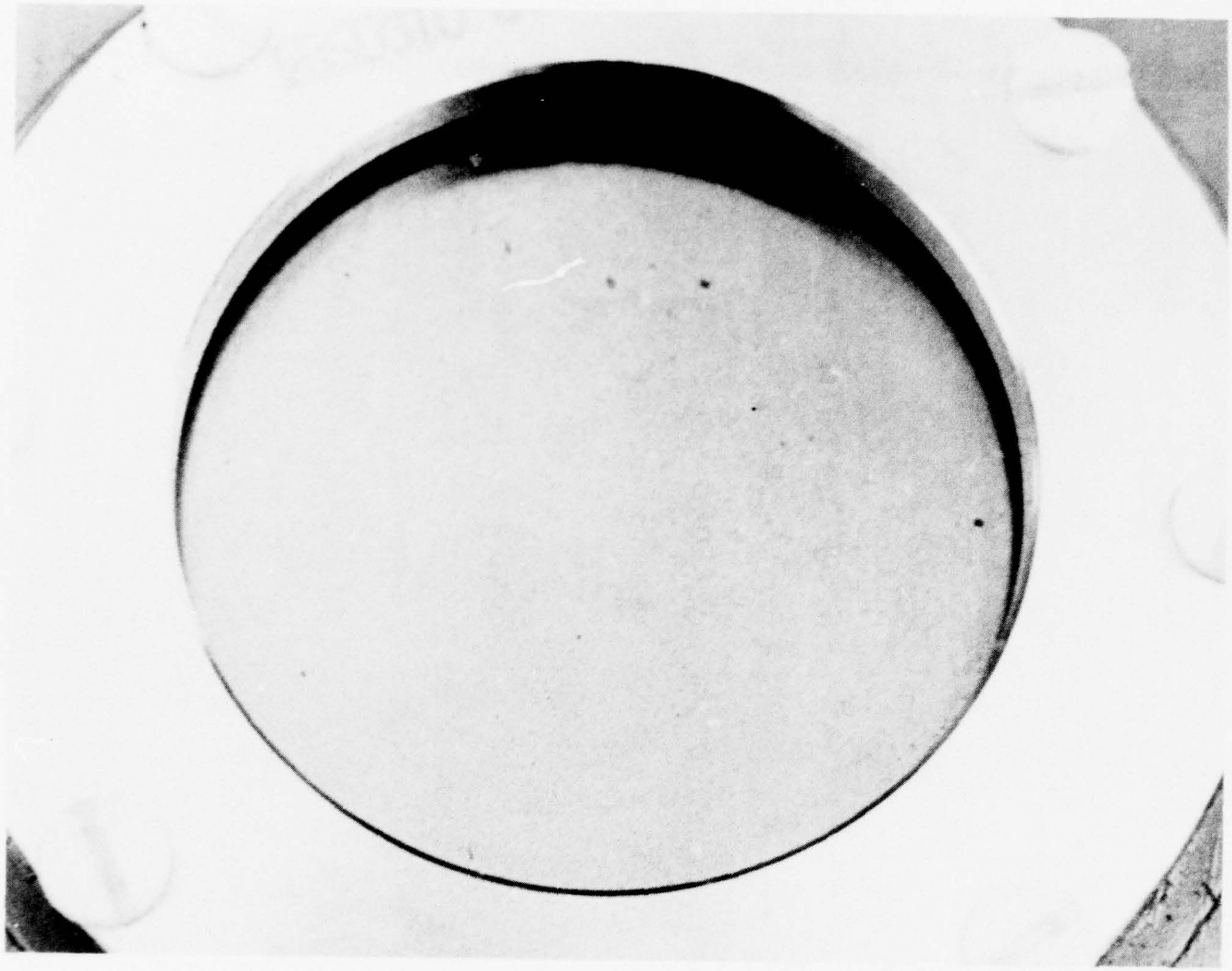


Figure 44. A specimen with the Exotic Materials AR coating after one month of testing with forced circulation in San Diego Bay.

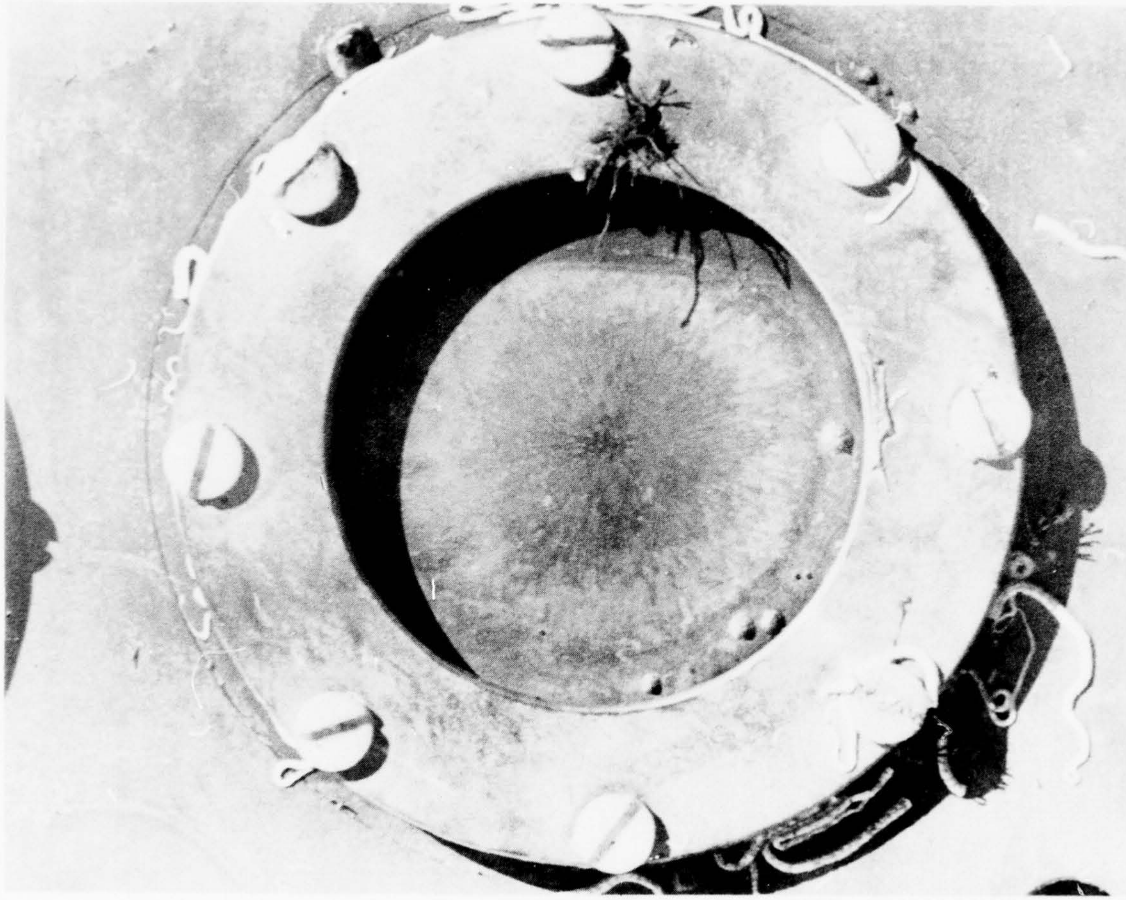


Figure 45. A specimen with the Exotic Materials AR coating after four months of testing with forced circulation in San Diego Bay.

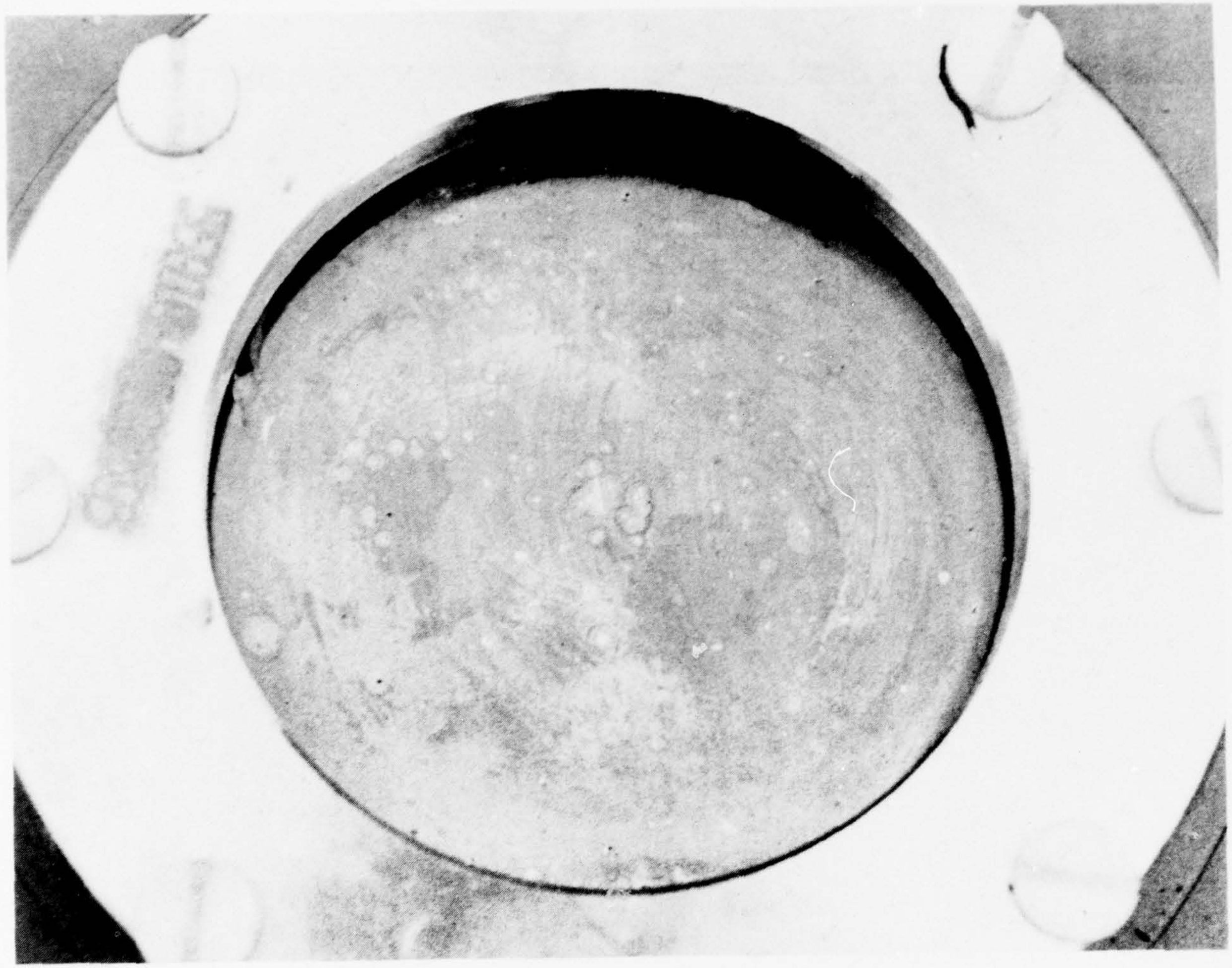


Figure 46. A specimen with the Optic Electronic AR coating after one month of testing with forced circulation in San Diego Bay.

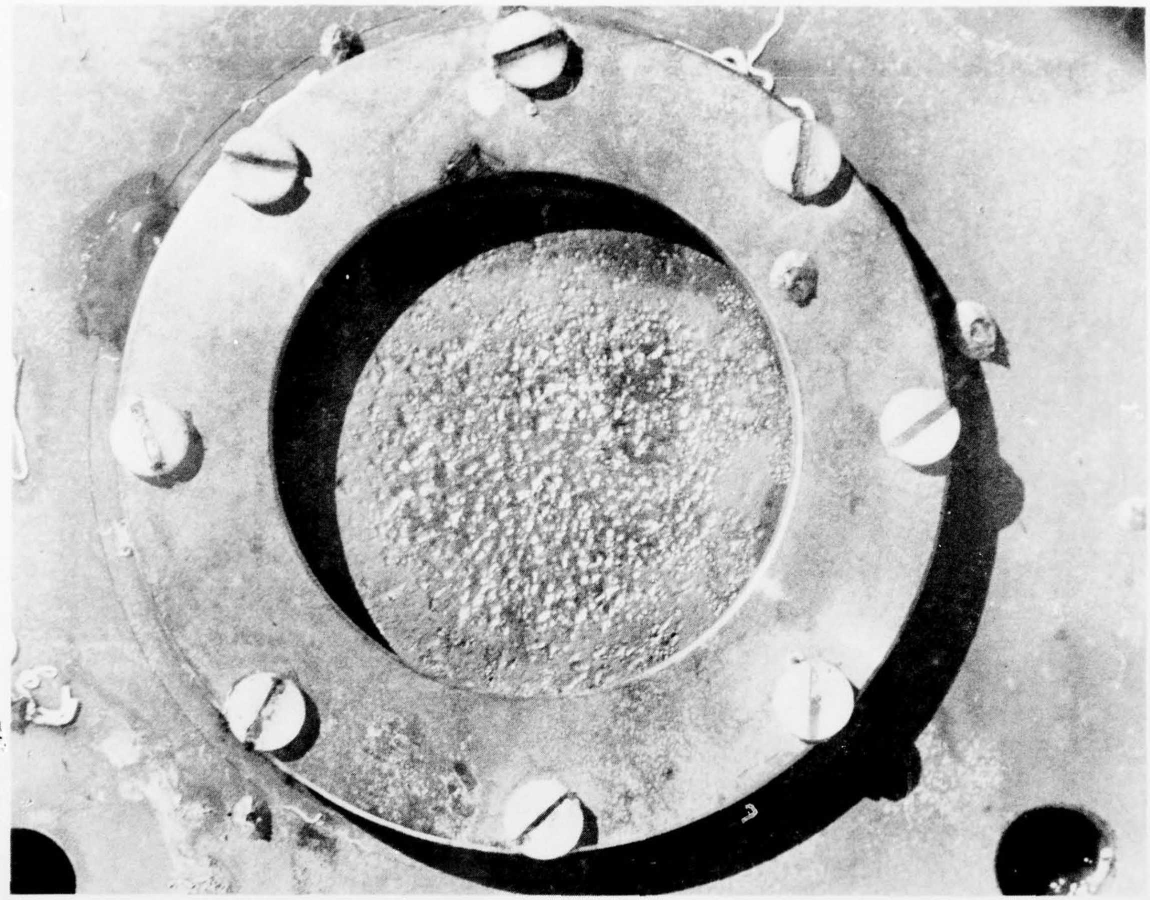


Figure 47. A specimen with the Optic Electronic AR coating after four months of testing with forced circulation in San Diego Bay.

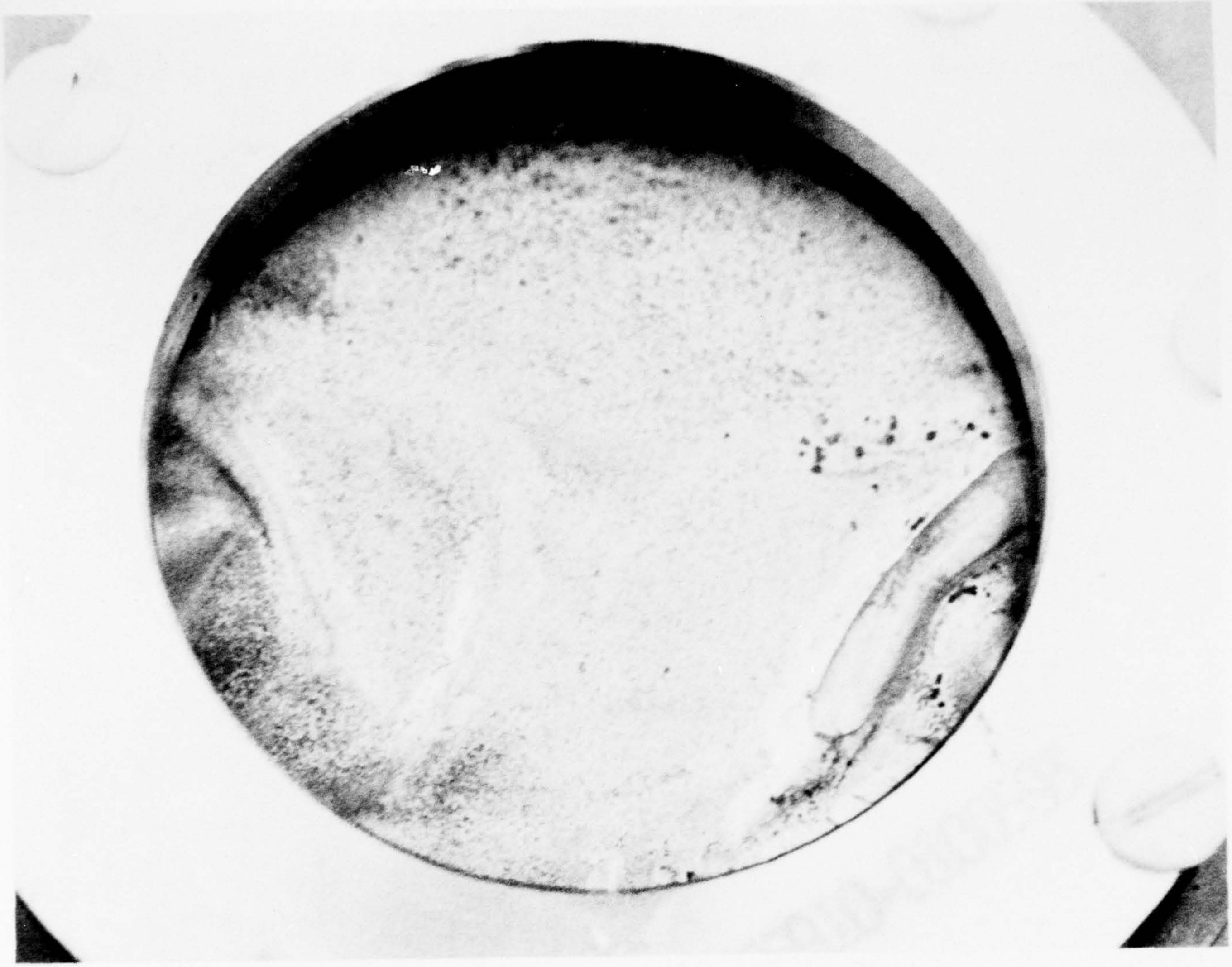


Figure 48. A specimen with the Honeywell PE/PP/PE plastic overlay after one month of testing with forced circulation in San Diego Bay.

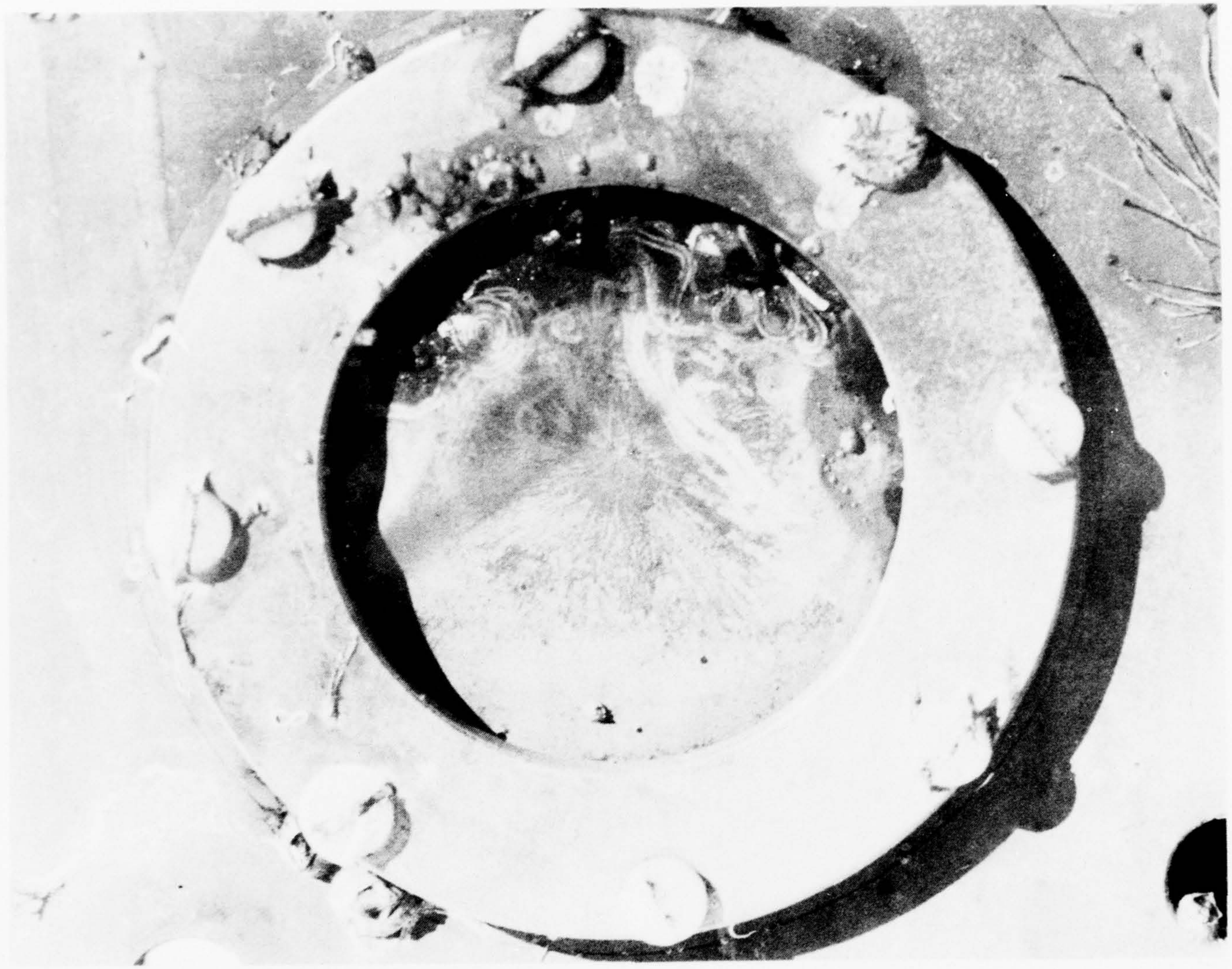


Figure 49. A specimen with the Honeywell PE/PP/PE plastic overlay after four months of testing with forced circulation in San Diego Bay.

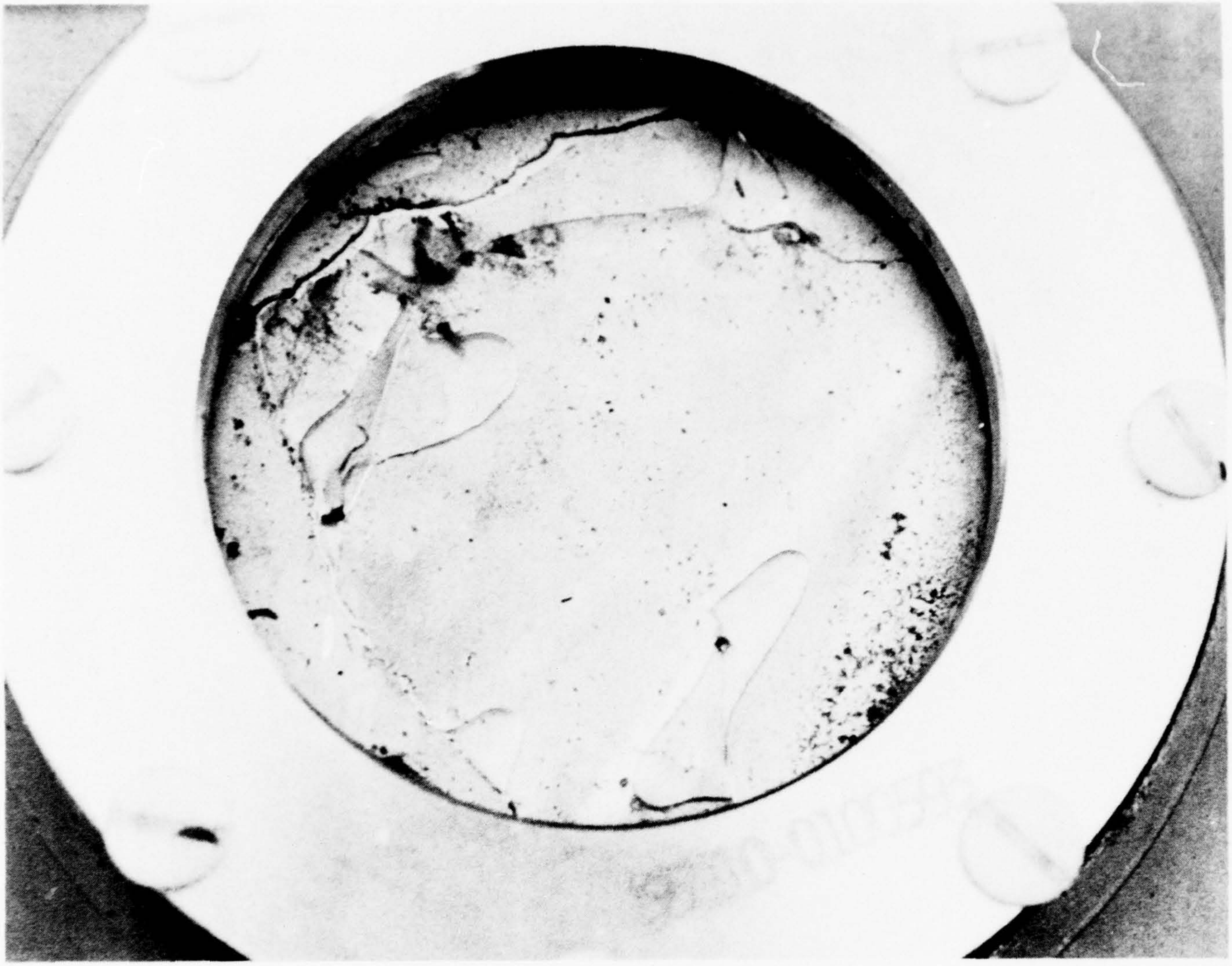


Figure 50. A specimen with the Lane Instrument PO plastic overlay after one month of testing with forced circulation in San Diego Bay.

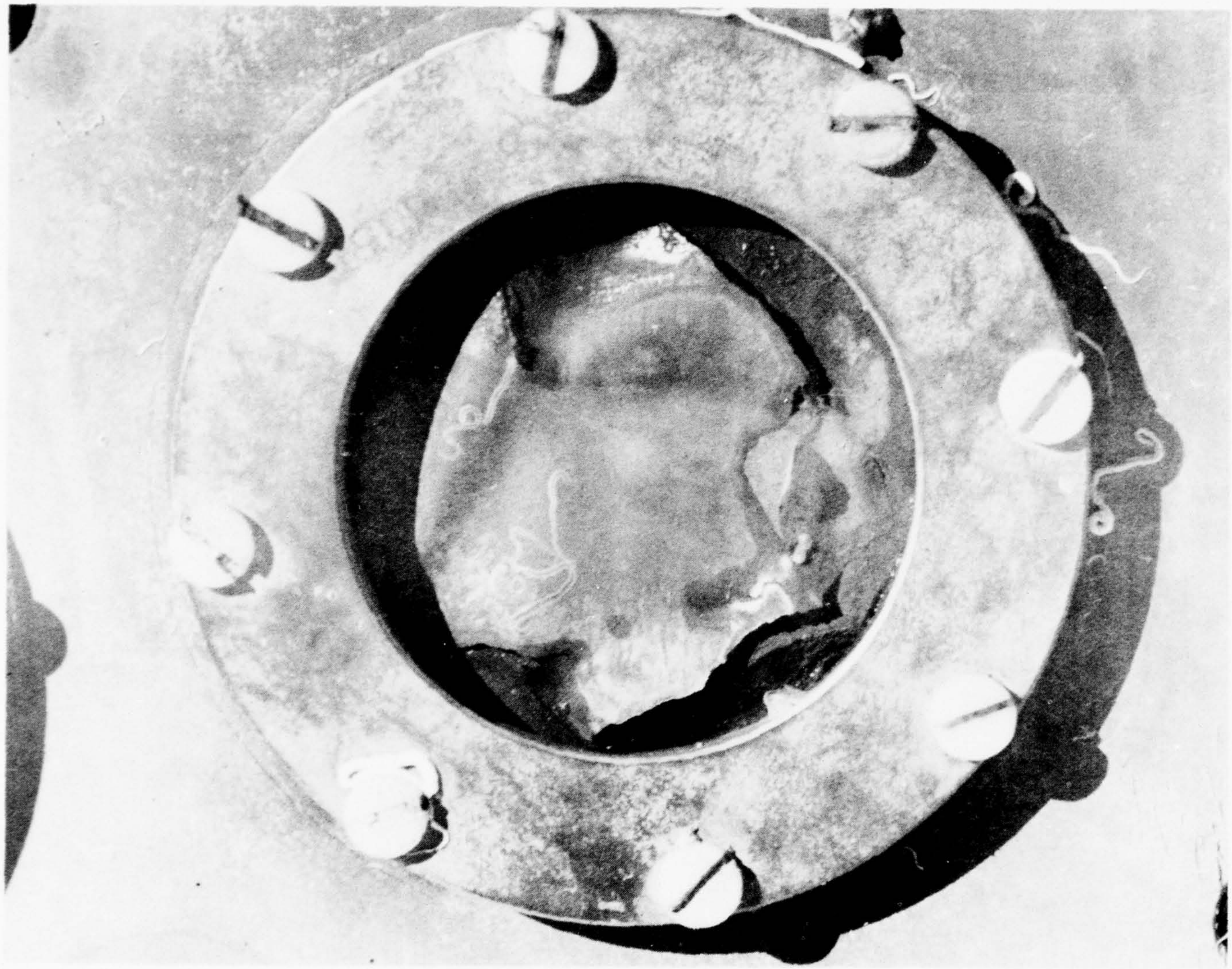


Figure 51. A specimen with the Lane Instrument PO plastic overlay after four months of testing with forced circulation in San Diego Bay.

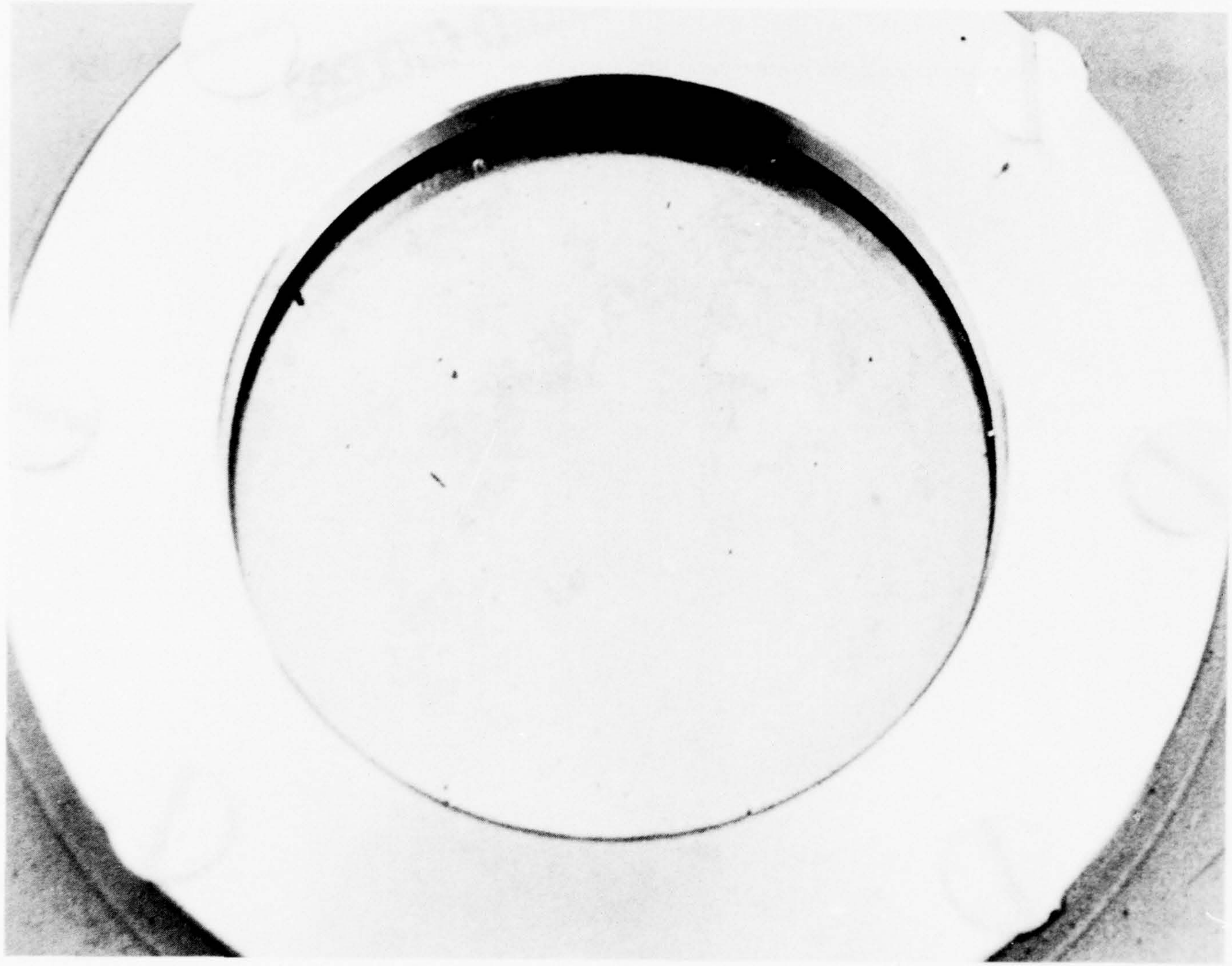


Figure 52. An uncoated germanium specimen after one month of testing with forced circulation in San Diego Bay.

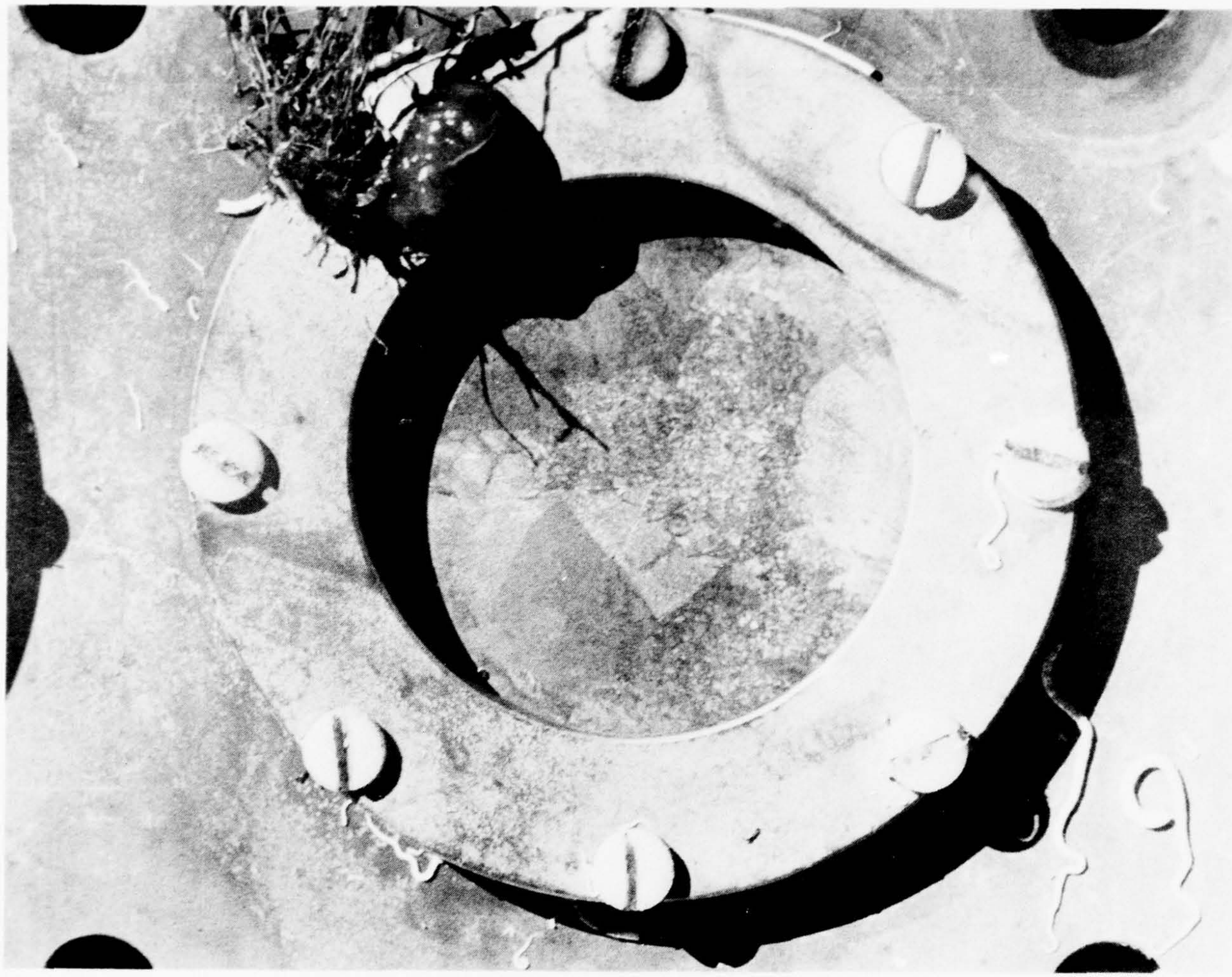


Figure 53. An uncoated germanium specimen after four months of testing with forced circulation in San Diego Bay.

Figure 54. A specimen of AMTIR-1 glass after one month of testing with forced circulation in San Diego Bay.

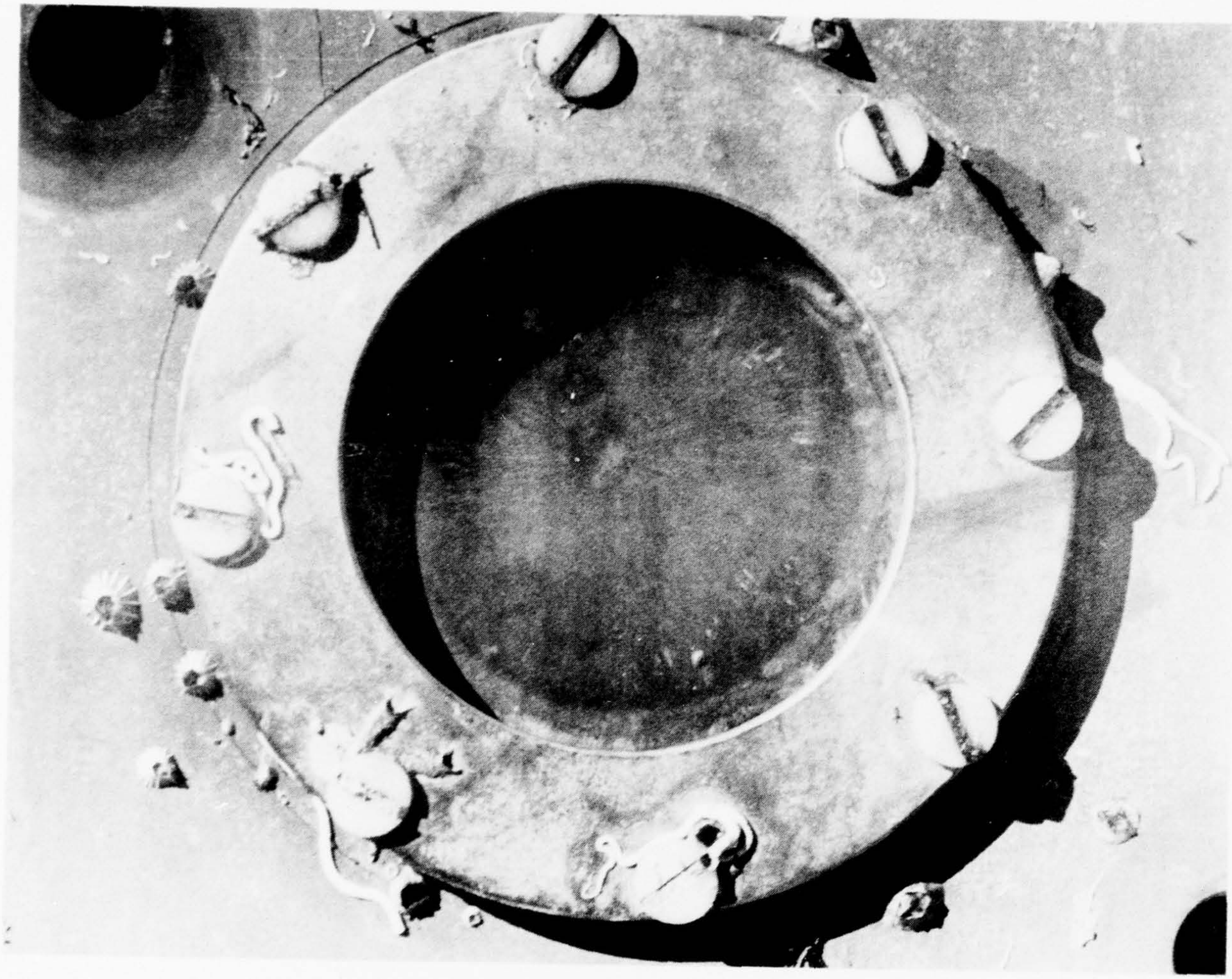


Figure 55. A specimen of AMTIR-1 glass after four months of testing with forced circulation in San Diego Bay.

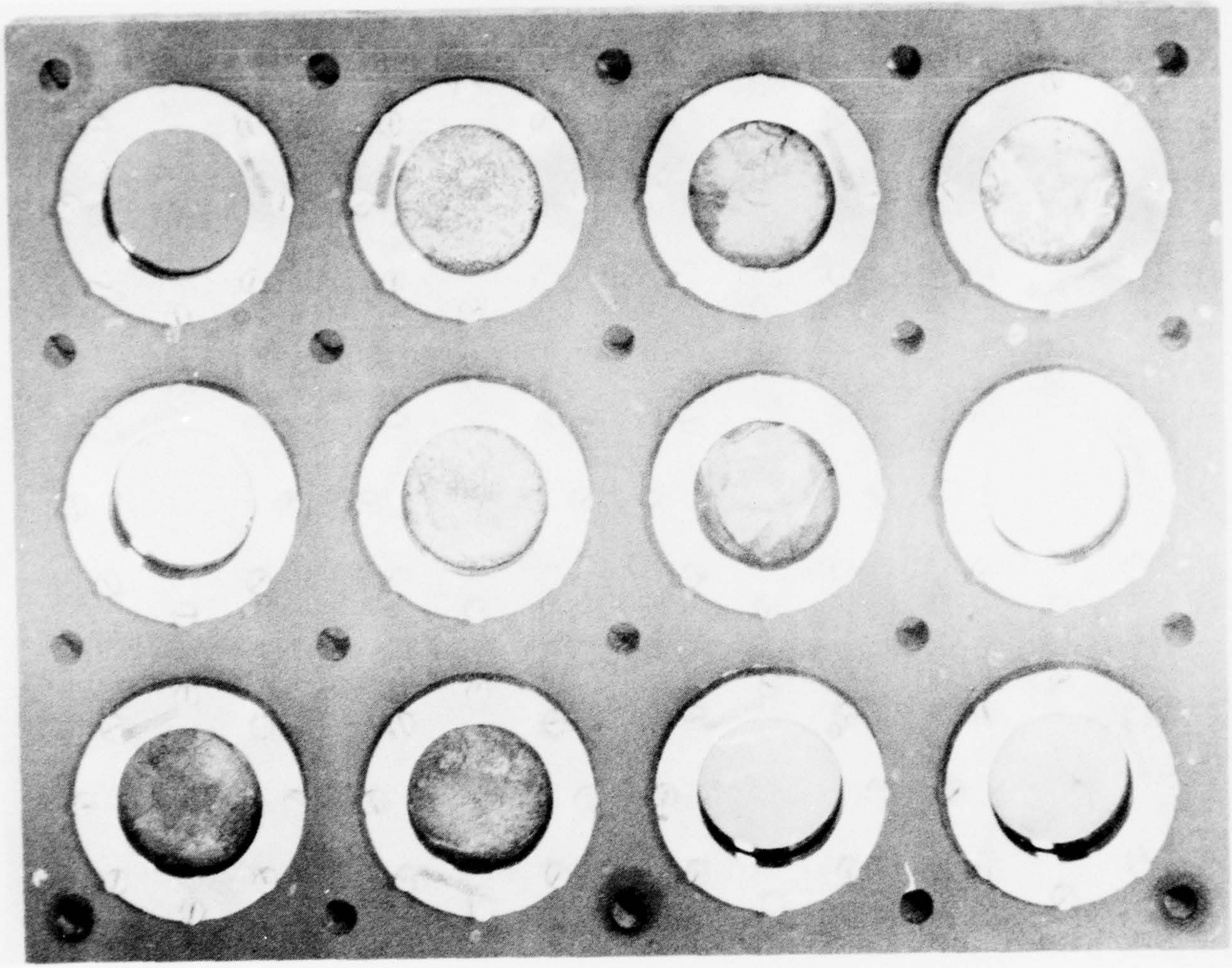


Figure 56. Test fixture B, utilizing forced circulation, after four months of testing. Surface growth has been removed to facilitate viewing the condition of the specimens.

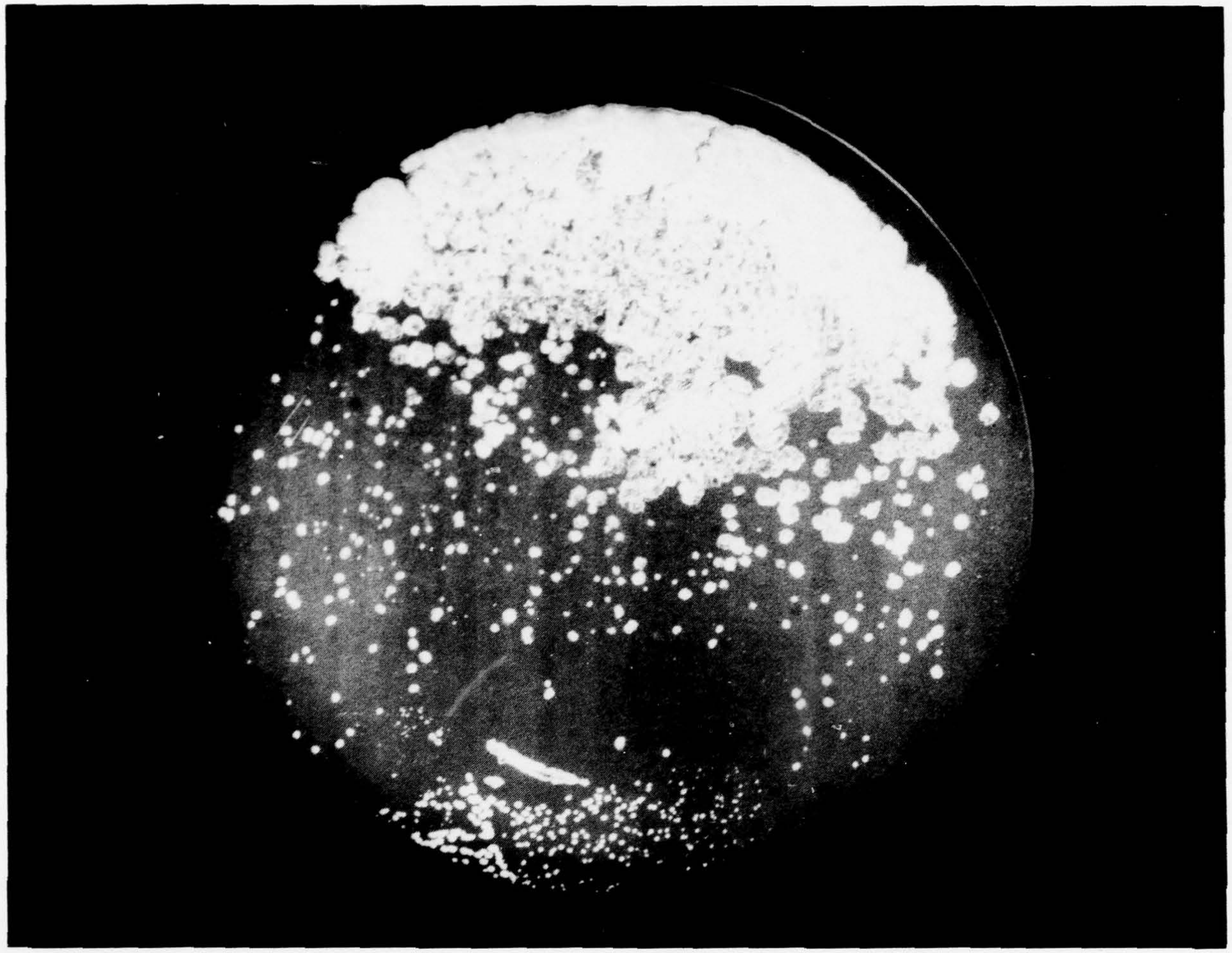


Figure 57. A specimen with the Optic Electronic AR coating, after indoor electric current testing for four hours; 0.5 amps at 60 volts.

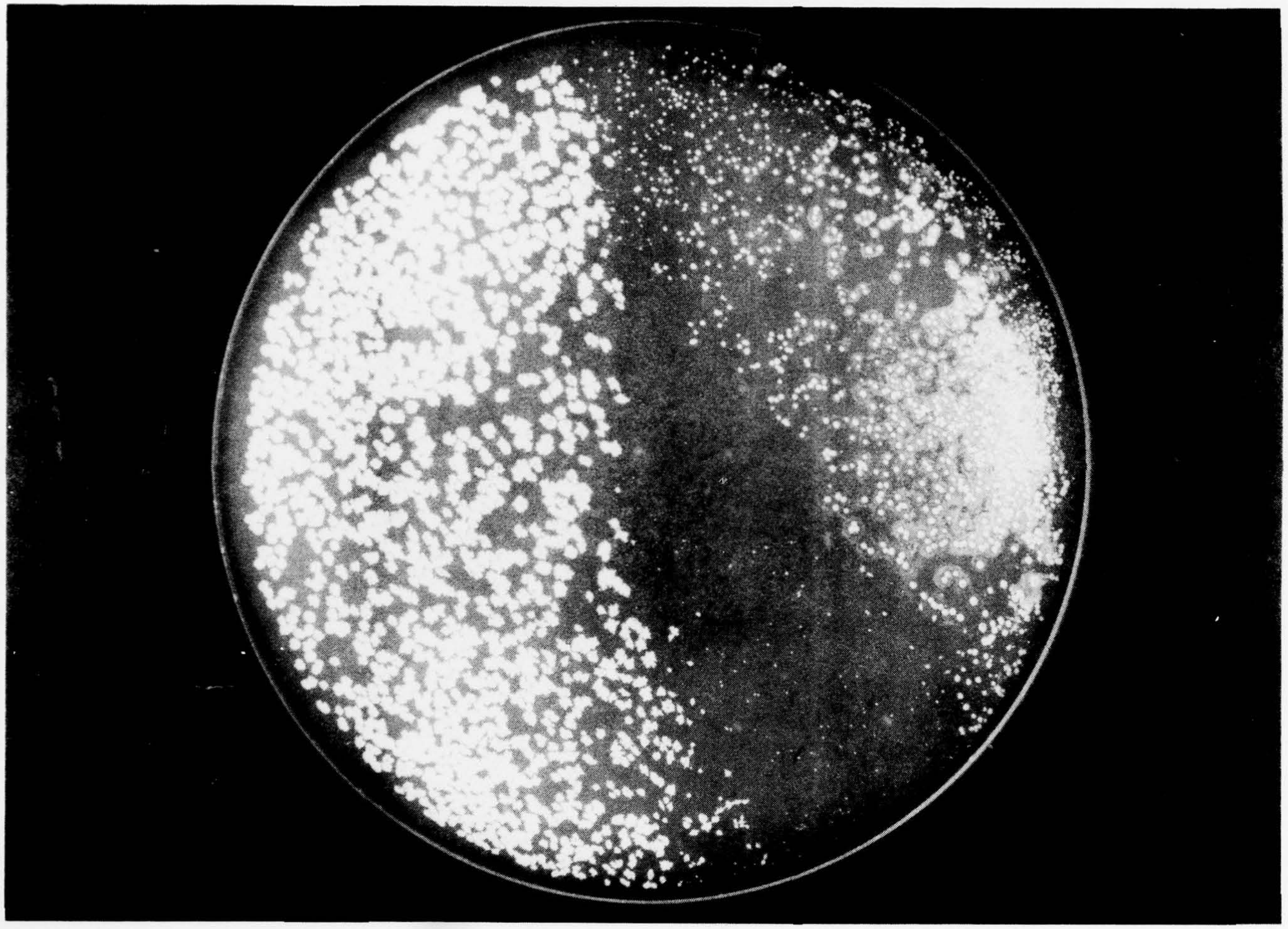


Figure 58. A specimen coated with Exotic Materials AR coating, after indoor electric current testing for four hours; 0.5 amps for 60 volts.

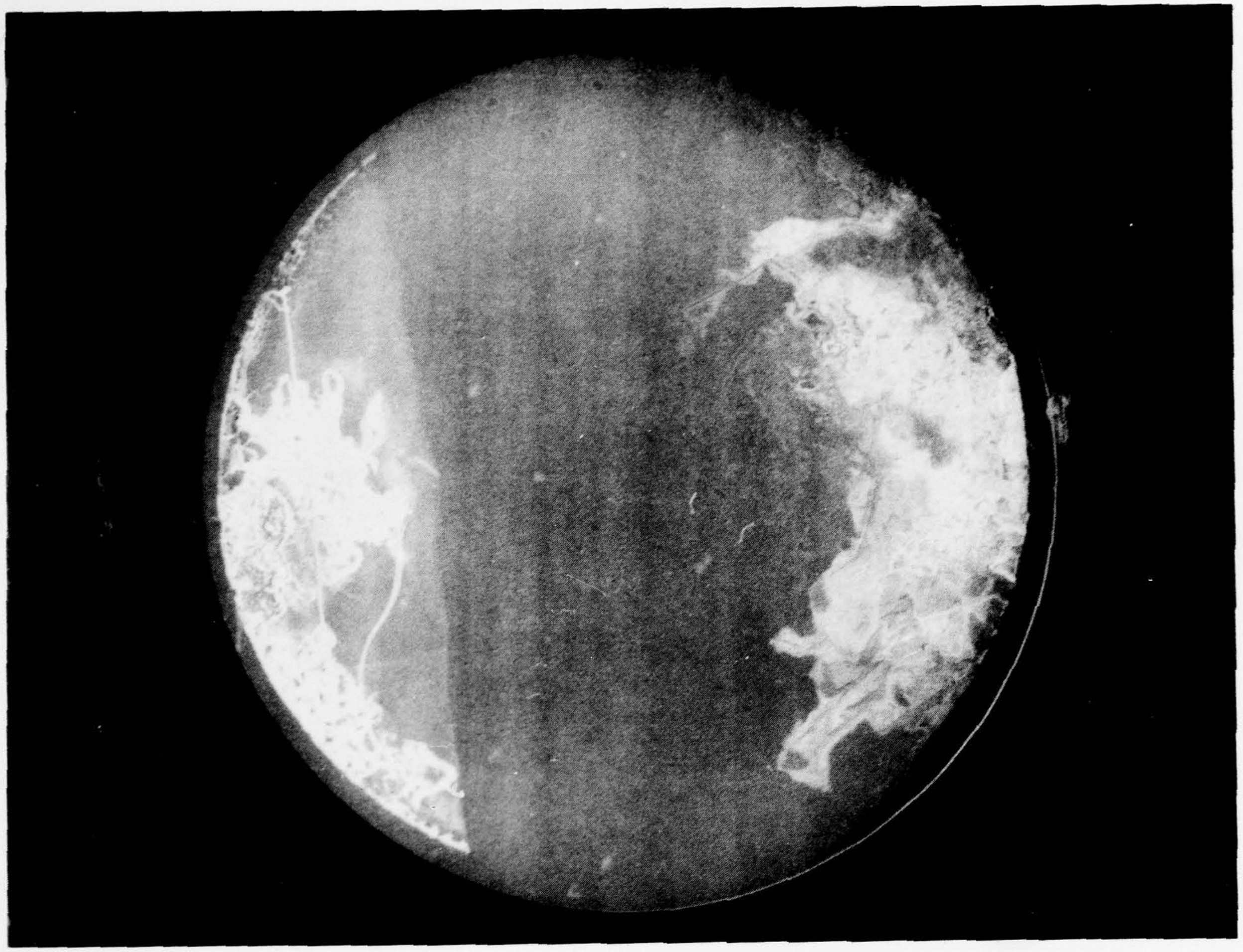


Figure 59. An uncoated germanium specimen after indoor electric current testing for four hours; 0.5 amps at 60 volts.

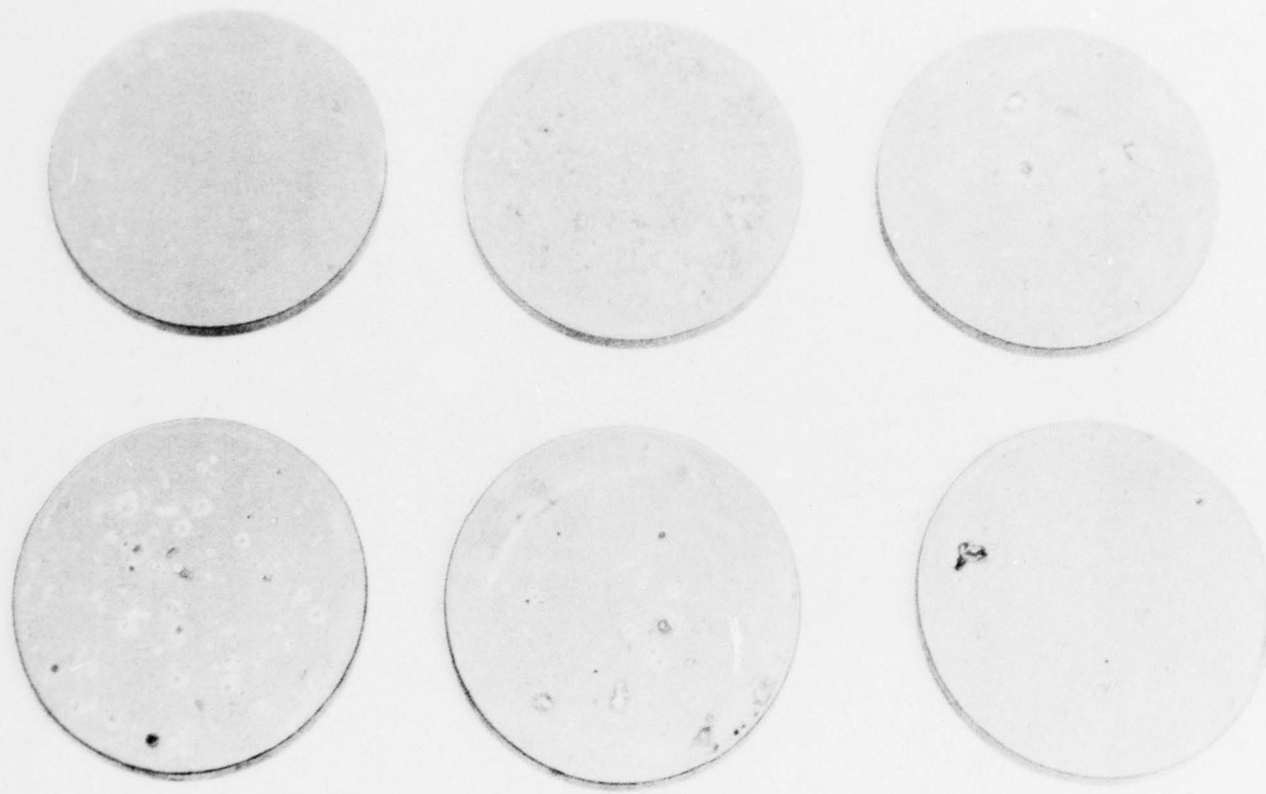


Figure 60. Specimens with Lane Instruments PO plastic overlay after 20 minutes of testing with electrical current in San Diego Bay; approximately 0.5 amps at 50 volts.

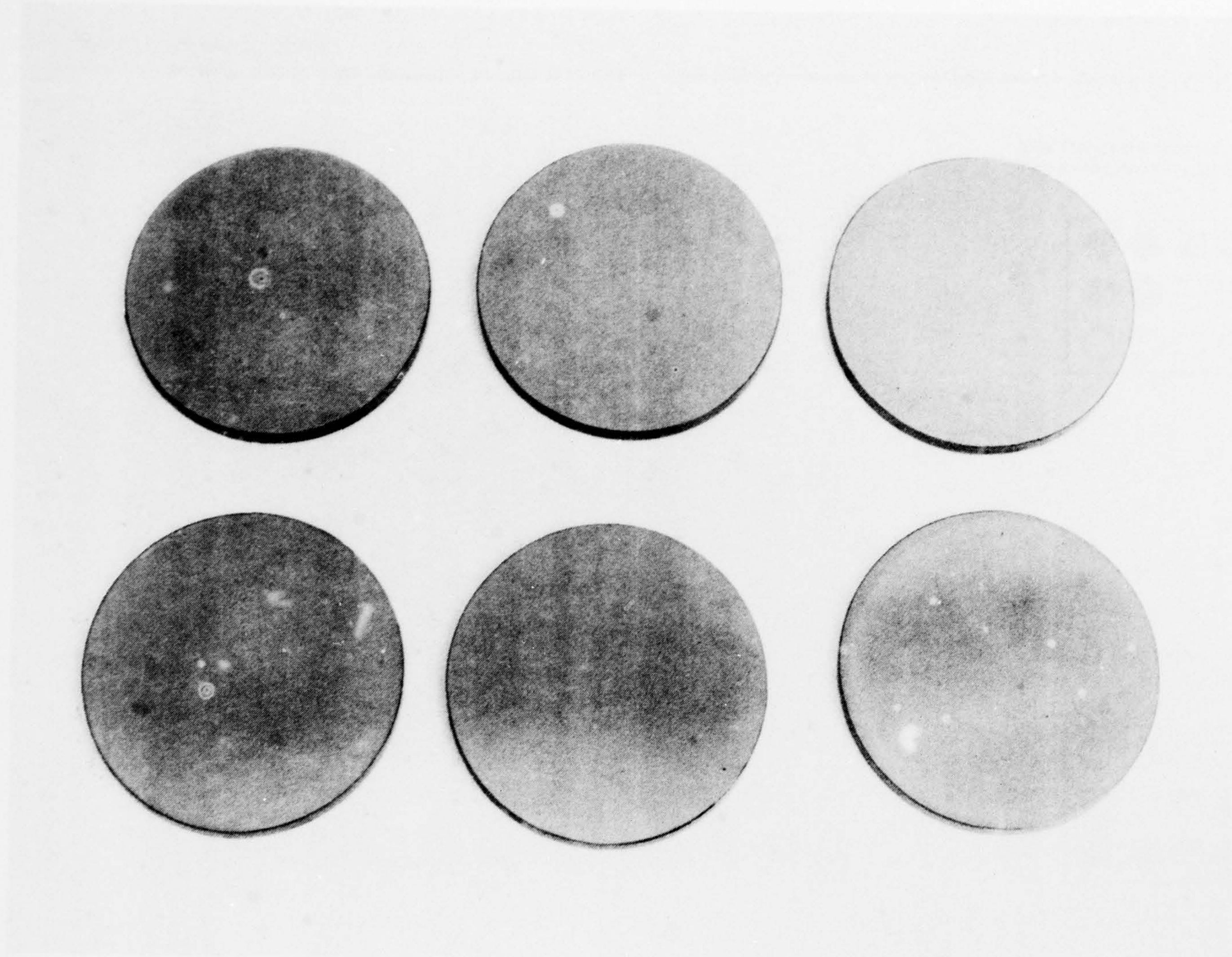
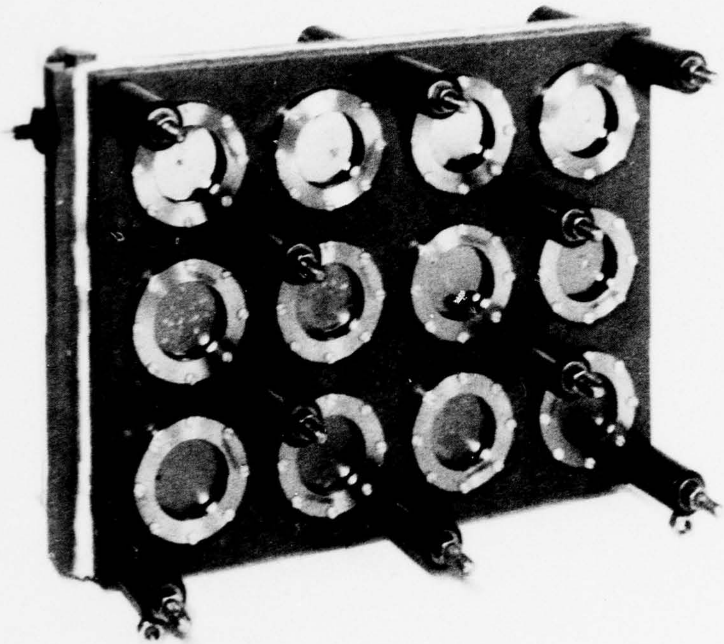
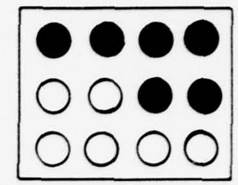


Figure 61. Specimens with the Honeywell PE/PP/PE plastic overlay after 20 minutes of electric current testing in San Diego Bay; 0.5 amps at 50 volts.





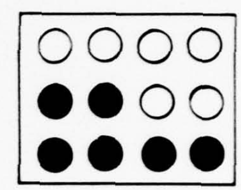


Figure 62. The specimens in test fixture C at the completion of current testing. For the final 40 minutes of testing, only the specimens with PE/PP/PE plastic overlay were connected in the current circuit.

Figure 63. Two specimens with PE/PP/PE plastic overlay that were electrically tested in the individual specimen test fixture in San Diego Bay for approximately 90 minutes each for 0.5 amps at 50 volts.

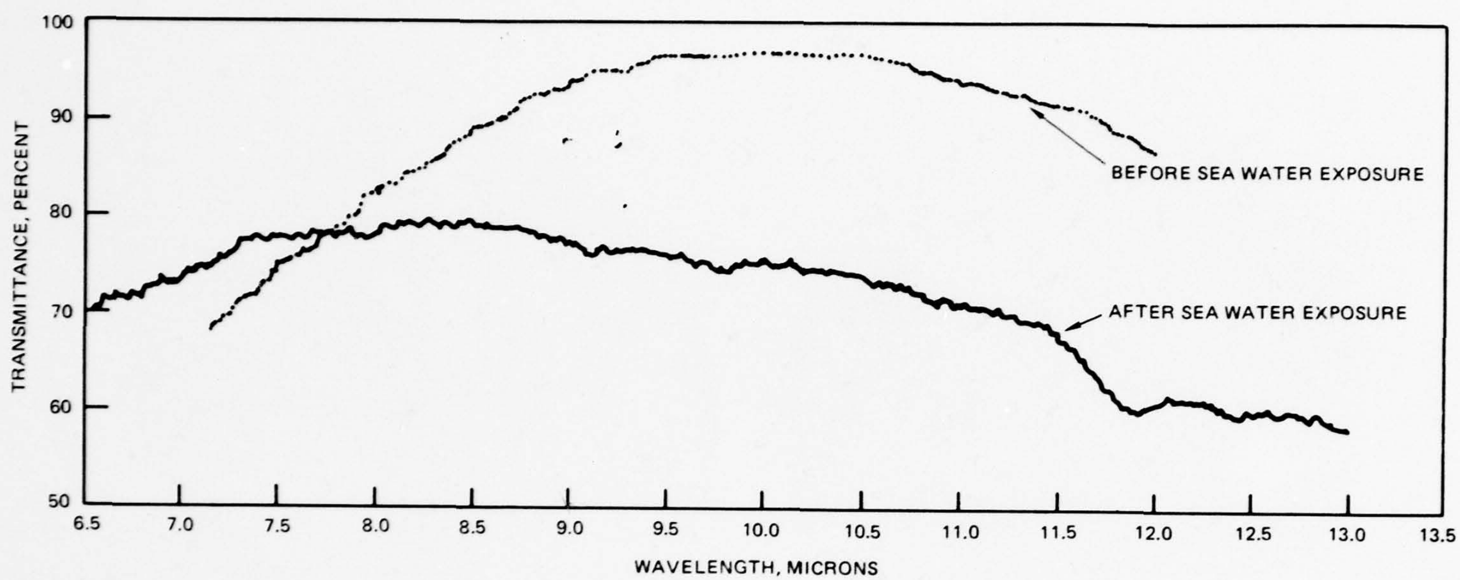


Figure 64. Transmittance of 0.25-inch-thick germanium specimens with Optic Electronic XF 27 single layer anti-reflection coating on both sides, before and after 4-month exposure to sea water with natural circulation.

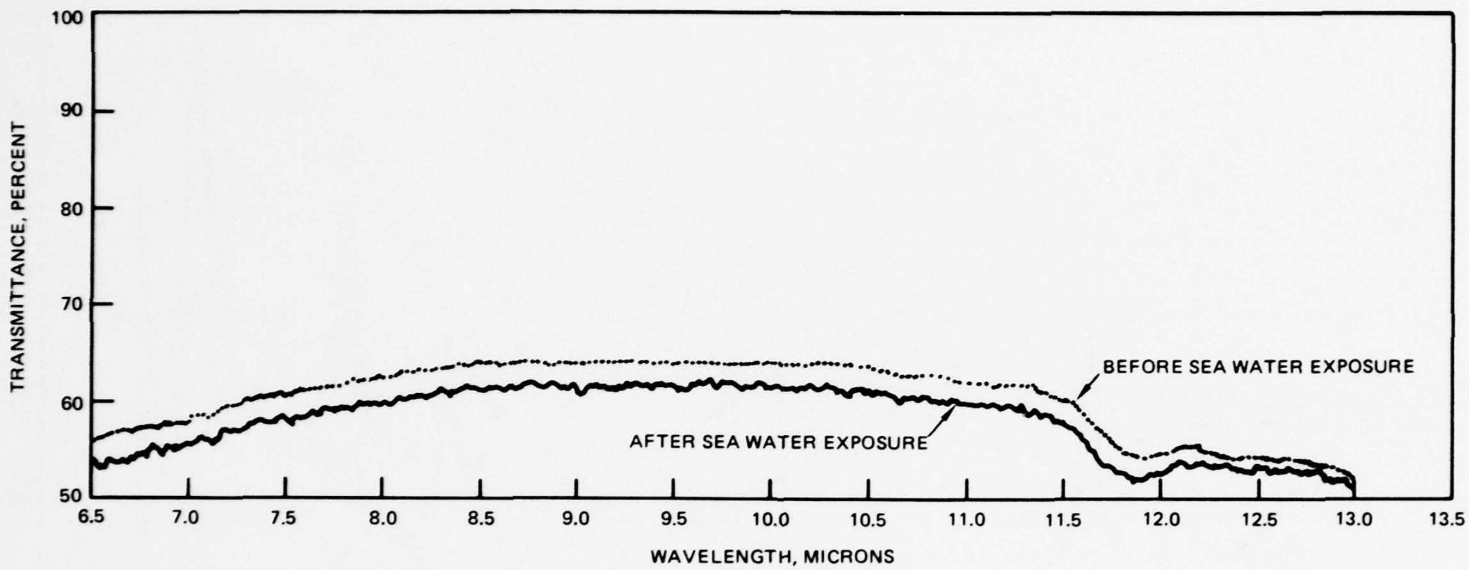


Figure 65. Transmittance of 0.25-inch-thick germanium specimen with Exotic Materials 40104 protected single layer anti-reflection coating on the face exposed to seawater, performed before and after 4-month exposure to sea water with natural circulation.

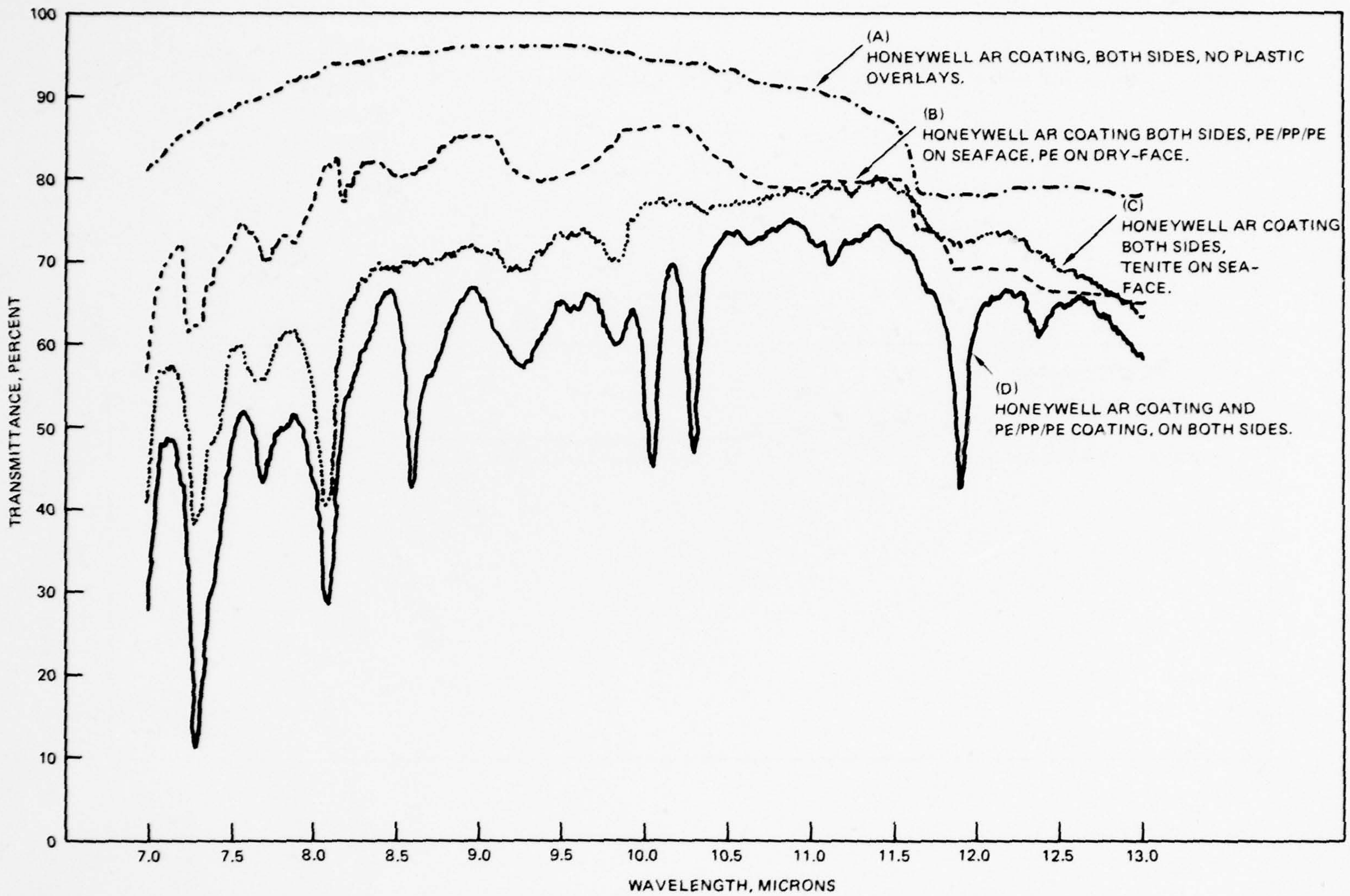


Figure 66. Comparison of plastic overlays applied by Honeywell to 0.25-inch-thick germanium specimens with proprietary Honeywell AR coatings on both faces. Specimen (A) no plastic overlays; Specimen (B) wetted face covered with PE/PP/PE and the dry face with polyethylene plastic overlays, respectively; Specimen (C) wetted face covered with a Tenite plastic overlay; Specimen (D) wetted and dry faces covered with PE/PP/PE plastic overlays. Transmission was not measured after exposure to sea water as the AR coatings on the wetted face were totally destroyed by sea water.

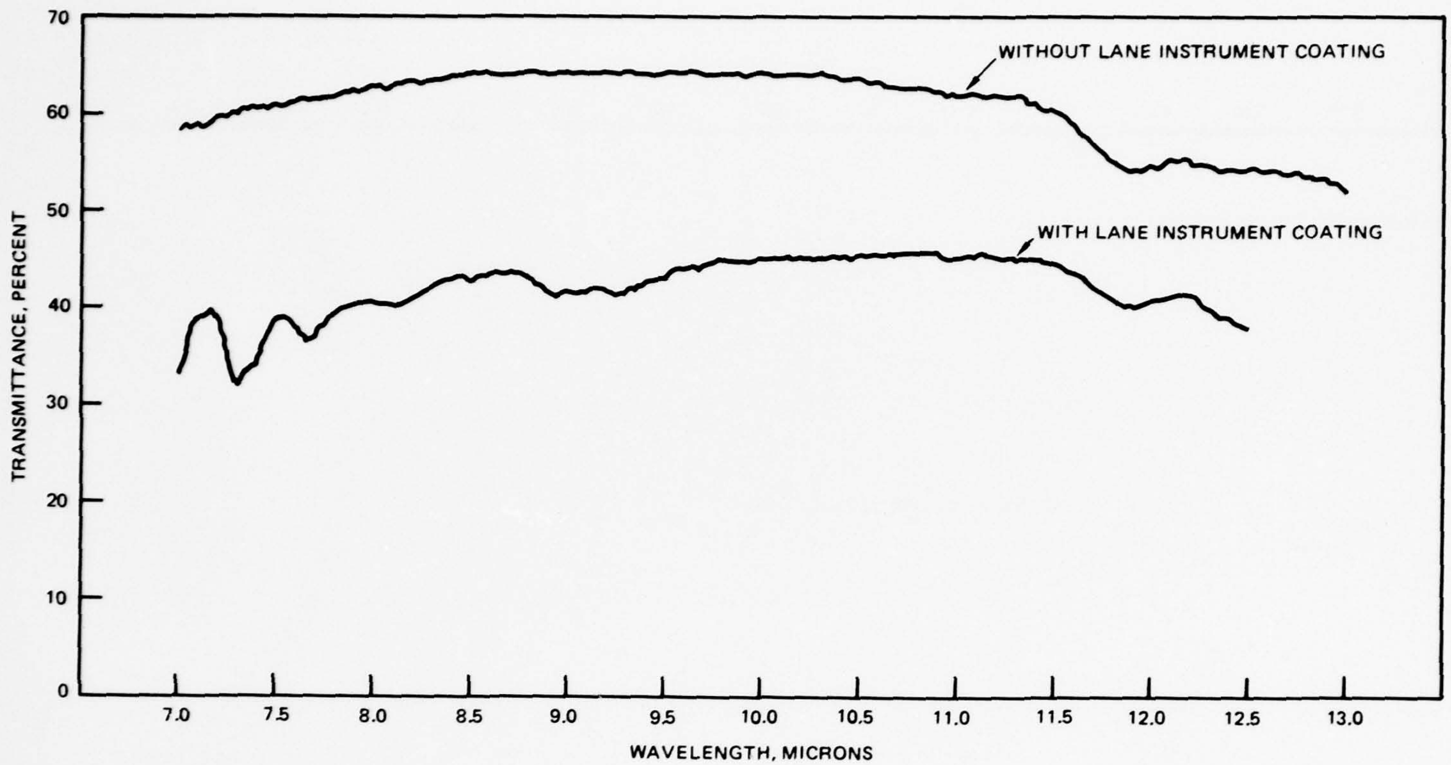


Figure 67. Transmittance of a 0.25-inch-thick germanium specimen coated on one surface with Exotic Material 40104 protected single layer anti-reflective coating prior to, and after super position of a PO overlay by Lane Instrument Co. Both readings were taken prior to seawater exposure. Transmission was not measured after exposure to sea water as the plastic overlay separated from the specimen and marine organisms were trapped behind the plastic overlay.

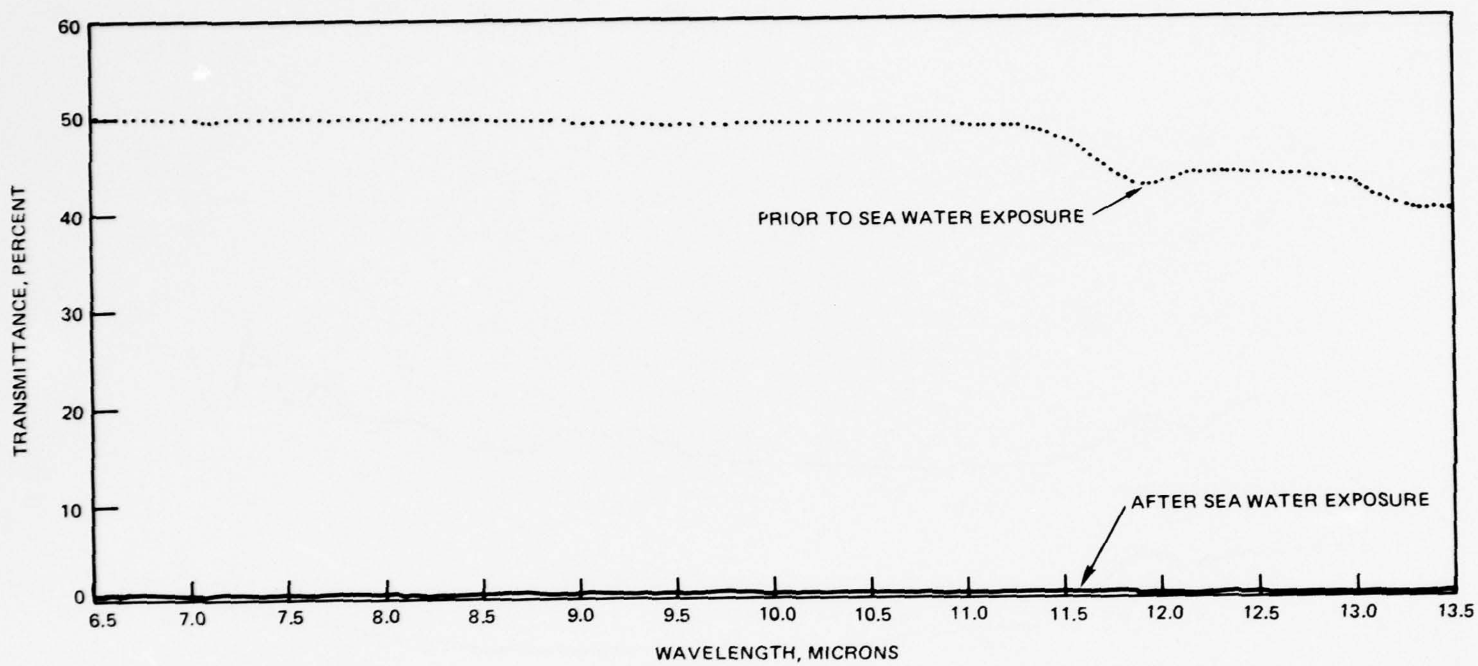


Figure 68. Transmittance of bare, 0.25-inch-thick, germanium specimen with polished surfaces, prior to and after four-month exposure to sea water with natural circulation.

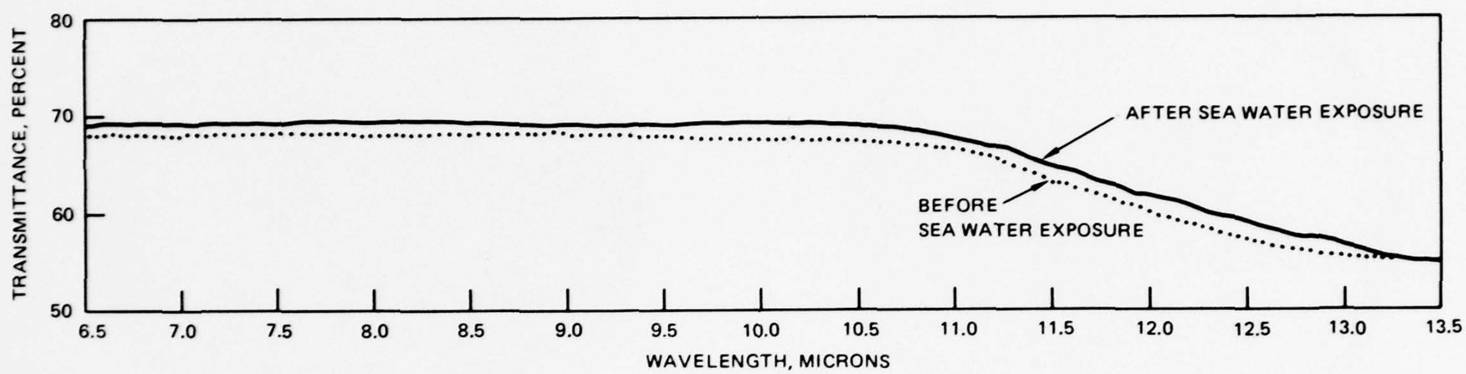


Figure 69. Transmittance of a bare 0.25-inch-thick AMTIR-1 chalcogenide glass specimen with polished surfaces, prior to and after four-month exposure to sea water with natural circulation.

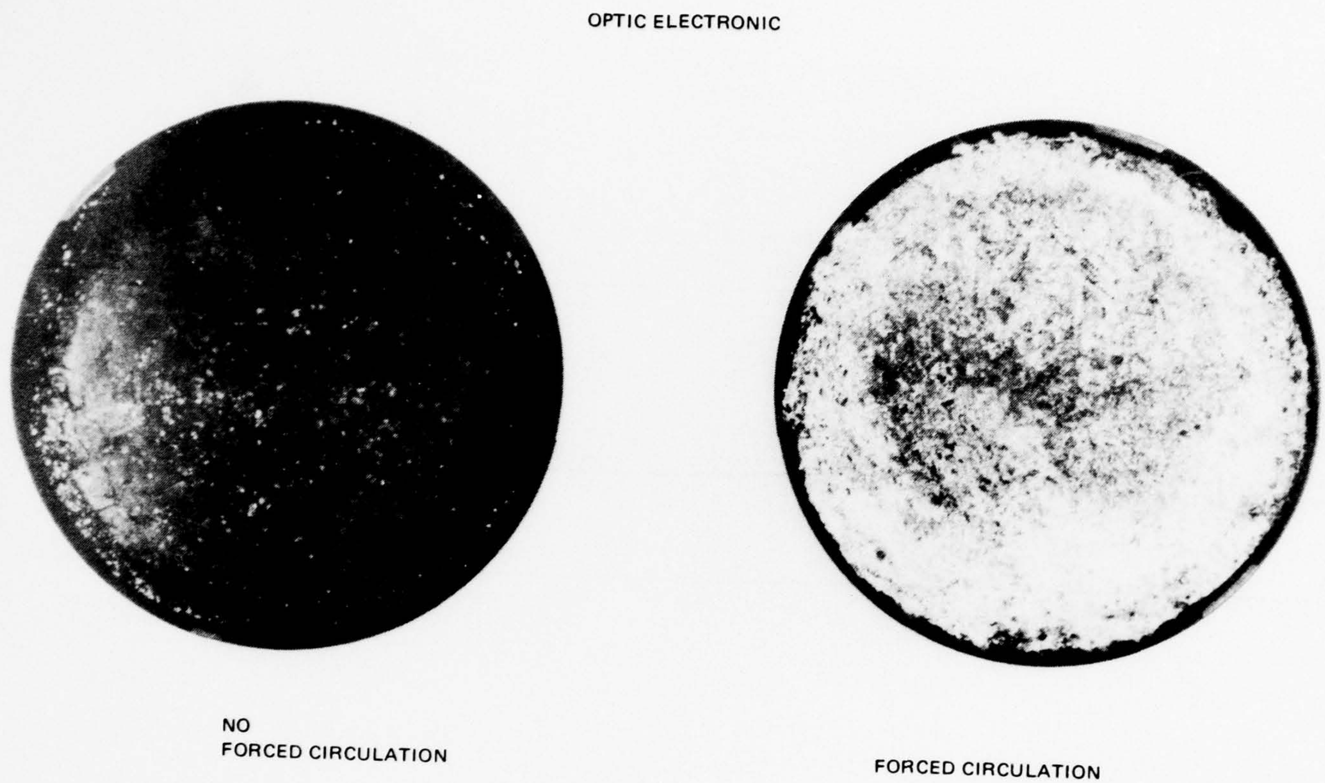


Figure 70. The effects of forced circulation contrasted with that of natural circulation, on a specimen with the Optic Electronic single layer anti-reflection coating XF 27.

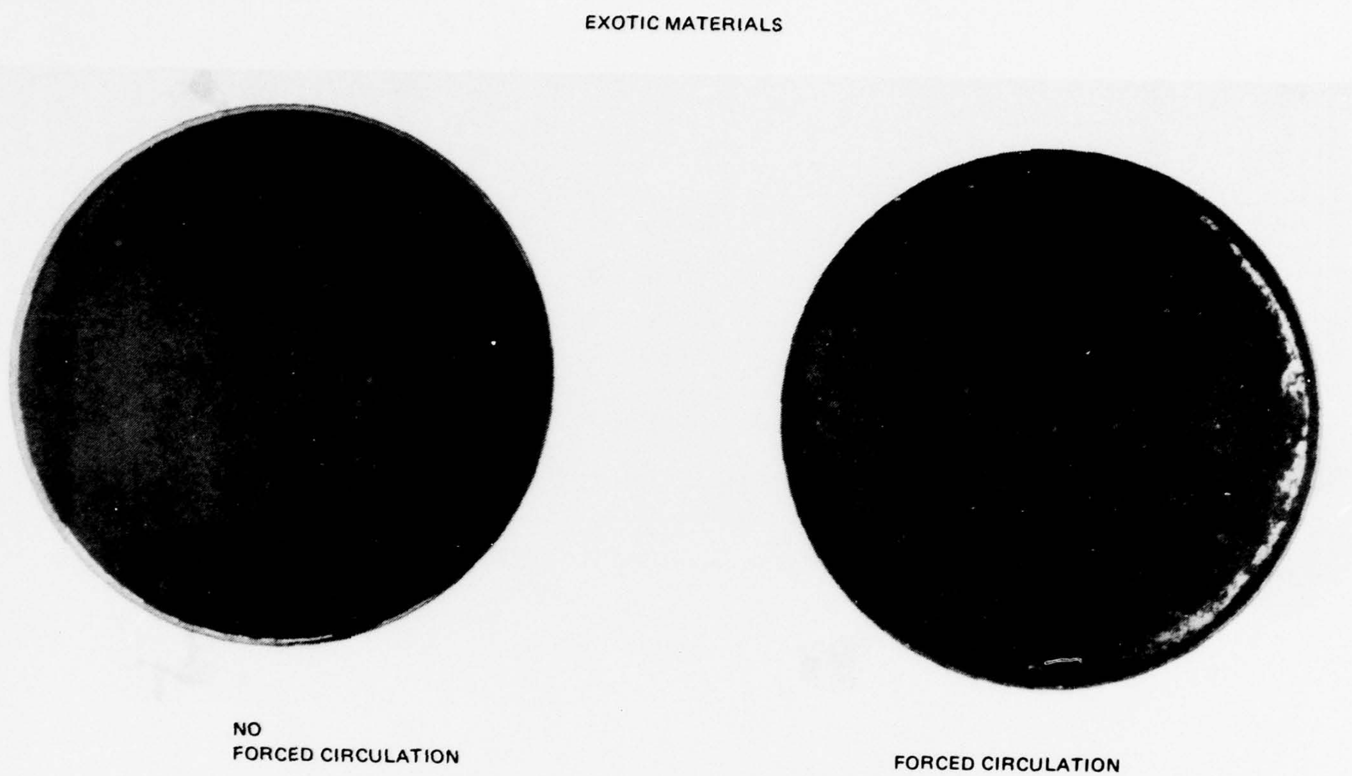


Figure 71. For the Exotic Materials single layer anti-reflection coating 40104 the increase in wear to the coating from forced circulation was negligible.